INFLUENCE OF REST PERIODS ON FATIGUE STRENGTH OF CONCRETE TESTED IN WATER

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CHAPTER I

INTRODUCTION

1.1 General Background

Offshore concrete structures have been constructed and are in operation in several parts of the world. The use of concrete structures for marine production, storage and transportation of hydrocarbons has introduced the material to an environment where existing knowledge has been limited. As offshore oil and gas production continues to move into deeper water locations, concrete structures are being subjected to greater hydrostatic pressure. Today gravity-based concrete structures have been installed where the water depth is 200 meters and structures are being planned for sites with much greater depth.

These ocean structures are subjected to cyclic loads from waves, wind, earthquakes and sheet ice in Arctic environments. Under these severe cyclic loading conditions, fatigue strength of concrete may become the limiting factor in the design of certain zones of these structures.

Most of the previous fatigue tests were of a simple nature with loads being applied between some constant minimum and maximum values until failure occurred. Such tests are not truly representative of the actual conditions to which a structural element may be subjected in a marine environment. In reality, structures are subjected to randomly varying loads, a combination of high-intensity, low-cycle fatigue loading during severe environmental conditions; low-intensity, high-cycle fatigue loading from moderate environmental conditions and nearly constant static loads when the ocean is calm.

Concrete is a porous material containing a complex system of channels and voids of different sizes. Some voids are initially filled with air; however, when concrete is exposed to a hydrostatic pressure, water can enter these voids, compressing and absorbing the air. Once water enters and fills the concrete pore system, an internal pore pressure will develop in the concrete. The presence of pore pressure may influence important design parameters such as compressive and fatigue strength of concrete.

The magnitude of pore pressure is dependent on the amount of water percolating into the concrete which in turn is related to the permeability. The permeability of concrete is strongly influenced by the water-cement ratio: the lower the ratio the less permeable the concrete will be. The bond between the paste and aggregate is improved when coarse aggregate is replaced with lightweight aggregate (LWA). Besides the low permeability, LWA concrete has its advantages when used to build marine structures. Some of the superior properties of LWA concrete are reduced weight which makes the structure easy to build and transport, excellent durability, and reduced microcracking because of the compatibility of its components. As a result, a high strength lightweight aggregate concrete would be the material of choice for marine structures. However, very few investigations on the behavior of high strength LWA concrete subjected to cyclic and sustained loading have been performed. Therefore, more testing on high strength LWA concrete is required to establish safe design criteria.

1.2 Purpose and Scope

The objectives of this study are to review the current state of knowledge on the influence of hydrostatic pressure on the strength of concrete subjected to cyclic and sustained loading and to experimentally investigate the same by means of fatigue tests on concrete under water interrupted with rest periods. Two types of concrete, an ND and a high strength LWA concrete, were employed in this study. Specimens were tested submerged in water with a confining pressure of either 0 or 1000 psi (0 or 7

MPa). The maximum stress level was 70 percent of the static compressive strength while the minimum stress level was 5 percent of the maximum stress level. The sustained stress during rest periods was equal to the mean of the maximum and minimum stresses. All specimens were loaded at a frequency of 1 Hz during fatigue loading.

CHAPTER II

LITERATURE REVIEW

2.1 Porosity Properties of Concrete

2.1.1 General

Concrete is a composite material consisting of coarse aggregate embedded in a matrix of mortar containing pores of different sizes. The void system in concrete comes from the presence of capillary pores, gel pores, air voids, and aggregate pores. In general, porosity is defined as the total volume of pores to the total volume of material.

2.1.2 Boundary porosity

Terzaghi [3] has discussed the fracture of porous, quasi-isotropic materials such as concrete and rocks subjected to unidimensional compression. He has pointed out on a vertical section through part of the surface of failure, the average normal stress on this surface is equal to zero; however, local tensile and compressive "scattering stresses" are present. Once the compressive load reaches a level where tensile scatter stresses are equal to bond strength of the material between grains, cracks begin to form approximately parallel to the load. Based on this principle, the increase in strength of a specimen with empty voids with an increasing confining pressure is because the grains themselves are very much stronger than the bond between the grains, and the strength of these grains is not influenced by confinement.

According to Terzaghi, when samples were tested with a watertight membrane, a confining pressure produced a precompression in the bond regions between grains;

hence cracking will not occur until tensile scatter stresses were equal to the bond strength of the material between grains. On the other hand, when water under pressure penetrates into the voids, the result is a reduction of stress carried by the bond material. Therefore, the overall compressive strength of the specimen is reduced. This reduction in strength depends on the degree of continuity of the intergranular bond. Terzaghi referred to this degree of continuity as "boundary porosity" and defined it as "the ratio of that part of the area of the potential surface failure which is in contact with the interstitial liquid and the total area of this surface." He also reported that fluid pressures up to several hundred atmospheres have no effect on the compressive strength of concrete without a membrane, whereas equal pressures acting on jacketed specimens increased the compressive strength considerably. Finally, he concluded that the boundary porosity of concrete was close to unity.

When concrete is subjected to load, microcracks start forming. The microcracks break down the bond areas in the concrete, resulting in an increased boundary porosity. Butler [4] concluded from his investigations, which consisted of tensile tests of concrete cylinders, that "the effective (boundary) porosity was initially rather less than unity but changed with increasing tensile stress, and hence cracking, to unity at failure."

2.2 Permeability of Concrete

Permeability is a measure of the rate of movement by a fluid in a porous medium. In general, the coefficient of permeability is defined by Darcy's law:

$$Q = AK_i$$

where

K = coefficient of permeability (m/s);

Q = rate of flow of fluid (m^3/s)

A = cross section area of flow (m^2); and

i = hydraulic gradient.

Permeability of concrete is normally measured in a laboratory by applying a water pressure to one face of a test specimen and then measuring the rate of flow through the concrete. In concretes with very low permeability, such as high strength and lightweight aggregate concretes, there may be no flow of water through the test specimen within a reasonable test period. The permeability of concrete is mainly determined by the permeability of the cement paste, except if very porous aggregates are used. The permeability of the paste is strongly influenced by the water-cement ratio. If the normal coarse aggregate is replaced by the LWA, the bond between the paste and aggregate is improved and the water transport in the contact zone between the aggregate and the paste will be significantly reduced.

The permeability of concrete depends on the mix design. Some of these parameters, such as coarse aggregate size, silica fume, and fly ash are summarized by Bjerkeli [2]. The permeability of concrete is significantly reduced if immersed in seawater. Haynes [5] and Buenfeld and Newsman [6] attributed this reduction in permeability to chemical reactions between ions in seawater and the hydrated cement which resulted in crystallization products that precipitate and block the pores in concrete.

Butler [4] summarized the permeability measurements obtained by several investigators. For an applied pressure between 0.35 and 2.80 Mpa on cylindrical specimens with diameters varying between 150 and 450 mm and lengths from 50 to 450 mm with water-cement ratios between 0.35 and 0.84, test durations varied from 24 to 408 hours. With this range of parameters, the permeability coefficients varied between 2×10^{-12} to 4436×10^{-12} m/s.

2.3 Pore pressure

2.3.1 General

Once a fluid starts percolating in a porous material, a pressure gradient will develop and pressure starts building up in the voids inside the material. Internal pressure is denoted "pore pressure" and will develop in all porous, permeable materials if subjected to fluid pressure.

One of the first investigations concerning the presence and influence of pore pressure upon concrete was conducted by Butler [2]. He studied the internal uplift in gravity dams caused by pore pressure. The uplift force was defined by Butler as "the force system attributable to the pressure of water in pores, fissures and joints within both the dam and its foundations."

Direct measurement of the pore pressure in concrete caused by the application of water pressure is difficult to obtain since pore pressure is strain-dependent as well as being heavily influenced by the degree of saturation [7].

2.3.2 Pore Pressure Response to Varying Loads

When a partly or fully saturated concrete is exposed to stresses (compressive), the result is a net reduction in volume and thus also a net reduction in pore volume. If loads are rapidly applied compared to the time for the water to flow a significant distance, a pressure buildup in concrete will occur. The magnitude of this pressure is strongly dependent on the degree of saturation of the concrete under stress. However, at a high stress level (about 75 to 90 percent of the ultimate load), increased pore pressure is less likely to occur because the volume of the specimen increases. The volumetric increase can be related to the development of extensive cracking.

If a permeable concrete becomes saturated with water and if the internal pore pressure is in equilibrium with the surrounding pressure, the influence of pore pressure on concrete is negligible. But once concrete is subjected to compressive stress, a positive pore pressure will be developed with respect to the confining pressure. This positive pore pressure will initially help to resist the applied load by reducing the stress in the granular structure; at the same time it will induce tensile stresses in directions perpendicular to the applied load. These tensile stresses will promote the formation of cracks which will cause the volume of concrete to increase.

This volume increase will cause the pore pressure to become negative with respect to the surrounding pressure. If loading is continued to failure, this negative pore pressure will tend to increase the apparent concrete strength. However, in the case of an impermeable concrete such as LWA concrete, global saturation will be difficult to achieve. Therefore, in high strength LWA concrete, only small zones are likely to become saturated and develop pore pressure. However, if microcracks started forming, water starts percolating through these cracks and may reach the interior of the core and exert pressure at microscopic zones where cracks are propagating.

2.4 Fatigue Strength of Concrete

2.4.1 General

Fatigue is that phenomenon by which a material is caused to fail by the application of repeated load which is not large enough to cause failure in a single application. Fatigue is a process of progressive permanent structural damage in a material; the structural changes may cumulate in cracks or complete failure after a sufficient number of cycles.

Fatigue data are usually presented graphically in the form of an S-N diagram, also known as the Whöler diagram. The ordinate S is the ratio of the maximum applied stress to the static strength, and the ordinate N is the number of cycles to failure (usually plotted to a logarithm scale).

Despite the early interest in metal fatigue, fatigue studies on concrete did not start until early 1900s. Norby [8] reports that one of the earliest investigations on compressive fatigue of concrete was that of Van Ornum [9] starting in 1903. One of the principal findings of his investigation was that the stress-strain curve varied with the number of cycles. The initially convex upward curve gradually straightens under repeated load and finally concaves upward near failure; the degree of concavity shows how close the test to approaching failure. Norby [8] and Murdock [10] have critically reviewed the work done on fatigue of concrete. Murdock's summary of the state of knowledge of compressive fatigue of concrete based on results of studies spanning some 50 years follow:

1. Failure in fatigue occurs in plain concrete subjected to repeated axial compressive loads.
2. The fatigue response, when expressed in terms of the static ultimate strength, is statistically independent of the nominal strength, frequency of repetition of the load, air entrainment or the type of aggregate employed.
3. The fatigue strength appears to be dependent on the range of the applied stress and increases as the range of stress is reduced.
4. The fatigue strength of ten million cycles may be taken at 55 percent of the static ultimate strength.
5. The modulus of elasticity is reduced by repetitive loading.

2.4.2 Effect of Submergence on Fatigue Strength

Offshore concrete structures are subjected to tcyclic loads from storm waves, wind, seismic loads, etc. Therefore, the fatigue life and the damage mechanism of concrete under a submerged condition should be considered in the structural design.

Several experimental studies on the fatigue behavior of concrete under a submerged condition have been conducted. A common conclusion from these studies is that fatigue life of concrete tested submerged in water is smaller than when tests are conducted in air.

Muguruma et al. [11] conducted some low cycle fatigue tests on two normal density ND high strength concretes. All specimens were 75 by 150 mm; water-cement ratios of 0.26 and 0.40 resulted in compressive strengths of 119 and 59 Mpa, respectively. After a curing period of 8 weeks in water, two-thirds of the specimens were removed from water and allowed to air dry for 6 to 10 weeks. One-half of the air dried specimens were tested in air; the remainder were tested resubmerged in water. Those specimens which were cured in water until the time of the test were removed from water and tested in air. Most specimens were tested at a frequency of 1 Hz while a few were tested at 10 Hz. Maximum stress levels of 70, 80, and 90 percent of the static compressive strength were employed for the lower water-cement ratio, and maximum stress levels of 80, 90, and 96 percent were used for the higher water-cement ratio. A minimum stress level of 5 percent of the static compressive strength was used throughout the tests.

Specimens which were air dried and tested in air had greater fatigue lives than specimens tested in water after air drying or tested in air after continuous water curing. The benefits of air drying and testing in air were most pronounced for specimens made with the higher water-cement ratio. According to the authors, these facts indicate that the wedge action of water trapped in the microcracks and voids accelerates the propagation of microcracks and results in an excessive reduction in the fatigue life of concrete under a submerged condition. Leeuwen and Siemes [12] conducted fatigue tests on plain concrete under submerged conditions. Although the literature is not available, the work has been summarized by Waagard [13]. He reported that submerged concrete has a shorter fatigue life than air-dried concrete, and extended storage time in water resulted in shorter fatigue life.

Viswanathan [14] conducted fatigue tests on about 120 3 by 6 in. and 4 by 8 in. saturated mortar cylinders. After curing in a fog room for 125 to 236 days, the specimens were oven-dried. Specimens were subsequently placed in chambers and subjected to high vacuum and saturated when deaired water was introduced to the chambers. The specimens remained in water until testing. Viswanathan estimated that the specimens achieved an average degree of saturation of about 97 percent. Specimens were then tested either submerged in water or in air. In the latter condition, the specimens were wrapped with a moist cloth to prevent surface drying. Specimens were tested using maximum stress levels of approximately 60, 70 or 80 percent of the static compressive strength and a minimum stress level of 10 percent of the static strength. Specimens were tested under a sinusoidal fatigue load with a frequency of 1 or 10 Hz. The results showed that :

1. Fatigue strength of saturated concrete was approximately 25 percent lower than dry concrete.
2. Larger specimens exhibited a slightly lower fatigue strength than smaller specimens,.
3. A higher rate of loading was found to increase the fatigue life of a specimen.

Waagard et al. [15] performed fatigue tests on specimens which were cored from a slab cured in an outside environment for two months. The cores had a diameter of 100 mm and a length of about 300 mm; the concrete had a 28-day cube strength of 70 Mpa. The concrete was made with lightweight coarse aggregates marketed under the brand name of type Liapor. Eighteen cores were tested in water under a hydrostatic pressure head of 60 m; of these, 6 cores had a single preexisting crack at midhight normal to the direction of the load. Seventeen cores were tested at a pressure head of 350 m; of these, 14 were solid and 3 were precracked. In addition, 8 of the solid cores were covered with a watertight membrane. A sinusoidal load was applied at a frequency of 1 Hz. The maximum stress levels ranged between 50 and 70 percent of the static compressive strength determined under the same pressure and exposure conditions as employed in the fatigue tests. The minimum stress level was 5 percent of the static compressive strength.

At a stress level of 60 percent, the cylinders with a membrane exhibited longer fatigue lives than unjacketed cores. At this stress level, although precracked cores had somewhat shorter lives than solid cores, the authors concluded that there was no significant effect from the precrack. However, this trend was not noticeable at higher stress levels, and increasing the confining pressure from 60 to 350 m increased the static strength by about 12 percent. Fatigue tests conducted with stress levels referenced to these static strengths indicated that unjacketed specimens tested with a higher pressure head had lower fatigue lives. The fatigue lives of cores dried for one week prior to test were significantly longer than specimens tested submerged at a 60 m pressure head.

Petkovic et al. [16] investigated the effect of moisture conditions during testing and curing on the fatigue strength of concrete. Two ND density concretes and one LWA concrete with compressive strengths of 7000, 10900, and 11600 psi (55, 75, and 80 Mpa), respectively, were tested. Three different sizes of cylinders were used: 50 by 150 mm, 100 by 300 mm, and 450 by 1350 mm. Three moisture conditions were employed: specimens were cured and tested in air, cured and tested in seawater, or sealed and tested in air. A frequency of 0.5 Hz was used for the largest specimens and 1 Hz for the two smaller specimens. The authors believed this small difference in frequency did not have a significant influence on the test results.

It was found that specimens with a diameter of 50 or 100 mm which were cured and tested in air yielded the longest fatigue lives; but specimens cured and tested in water resulted in the lowest fatigue lives. When the medium size ND concrete specimens were tested dry, the fatigue life increased from several thousand cycles to several hundred thousand cycles compared to those tested in water; on the other hand, the fatigue life of the LWA concrete increased only slightly. Tests performed on sealed ND specimens yielded fatigue lives only slightly greater than tests in water, whereas similar fatigue lives were found for the LWA concrete when tested either in air or in a sealed conditions. The fatigue lives of large specimens with a diameter of 450 mm were found to be unaffected by the moisture conditions.

Shaheen [17] conducted fatigue tests on high strength LWA concrete cores which had a 28-day compressive strength of 8580 psi (59.2 Mpa). All specimens were approximately 6 by 12 in. (150 by 300 mm). Most cores were stored in a fog room until time of testing. For specimens which were tested in the air-dry condition, they were exposed to ambient laboratory air with a humidity of approximately 40 percent for two months prior to testing. Specimens were tested in air or in water under a confining pressure of either 0, 3.5, or 7.0 Mpa (0, 500, or 1000 psi). The maximum stress level was 60, 70, or 80 percent of the static compressive strength. This strength was the average obtained from four cores loaded at a rate of 250 Kpa/s while submerged in water at zero pressure. The minimum stress level was 5 percent of the maximum stress level. Most specimens were loaded at a frequency of 1 Hz except for three specimens, for which a frequency of 0.1 Hz was employed. Before the initiation of fatigue tests, a 24-hour soak period was observed after the application of the confining pressure. For cores tested dry or submerged without a confining pressure, no soak period was employed.

It was found that fatigue lives of specimens tested in a submerged condition were significantly less than for specimens tested in a dry condition. Specimens tested in water at zero confining pressure exhibited the shortest fatigue lives. Specimens tested with a confining pressure of 3.5 and 7.0 Mpa exhibited similar fatigue lives which were between the dry and zero pressure conditions. Shaheen observed a reduction of approximately 32 percent of the arithmetic mean fatigue life of specimens loaded at a frequency of 0.1 Hz compared to that of 1 Hz when tested at a confining pressure of 3.5 Mpa and a maximum stress level of 80 percent.

2.4.3 Failure Mechanism of Concrete Under Cyclic Loads

Studies of the mechanics of crack formation and growth have largely concentrated on short-term monotonic loading; the mechanics of crack formation under sustained or time-varying conditions has received little attention. Bond cracks exist even before the concrete is subjected to any load. These cracks can be caused by shrinkage of cement paste from hydration or drying .

Fatigue failure of concrete is complex and strongly related to the presence of stress, the repeating nature of some stresses, and the presence of discontinuities such as heterogeneity of the material and cracks. The presence of aggregate particles embedded in a softer mortar matrix introduces a weak link in the system which results in a nonuniform internal stress state when concrete is loaded. In addition to aggregates, voids and other flaws such as initial microcracks act as stress raisers, thereby serving as a potential locations for formation of new cracks at stresses well below the ultimate strength. The critical regions of high stress occur near the tip of macrocracks. These stresses can form microcracks, which then relieve the high stresses at the macrocrack tip. Cyclic stresses modify the formation of microcracks and cause slow, stable growth of macrocracks until an unstable condition is reached. Shah and Chandra [18] studied the failure mechanism of concrete specimens, 2 by 2 by 6 in. (5 by 5 by 15 cm) with a water-cement ratio of 0.54 and an average compressive strength of 4.58 ksi. The maximum loads varied from 60 to 90 percent of the ultimate static load and the minimum load was kept at 10 percent of the static strength. They observed two stages of crack growth. For stress levels of 70 percent and lower, cyclic loading resulted in a stage 1 crack growth. During this stage a fairly stable and relatively small rate of crack growth occurred. Stage 2 crack growth was associated with specimens loaded at stress levels of 80 percent and higher. During this stage of crack growth, the volumetric strain increased sharply. The authors noted that microcracking consisted of extensive branching of cracks in the matrix, plus substantial amount of cracking at aggregate-paste interfaces. They found that at about 90 percent of the total cycles to failure, cracking—obtained by multiplying the total length of cracks with the observed average width of the cracks in a given sliced concrete section—was about three times greater as that created by a short-time application of the same load.

Holmen [19] tested cylindrical concrete specimens (100 by 200 mm) under repetitive loading with a minimum stress level of 5 percent and a maximum stress level that ranged from 60 to 95 percent of the static compressive strength. The mix proportions were 1:3.32:2.65 by weight for the cement, fine aggregate and coarse aggregate, respectively. The water-cement ratio was 0.55., the 28-day cube strength was approximately 40 Mpa, and the loading frequency was 5 Hz.

Results indicated that the total strain—the author defined it as the sum of elastic and inelastic strain—gradually increases with the number of cycles. This increase consisted of three different stages: A rapid increase in the first 10 percent of the fatigue life (arithmetic), a uniform increase from 10 to about 80 percent and then a rapid increase until failure. He also observed a reduction in the secant modulus of elasticity during fatigue life. It seems that, at any cycle, the lower the stress level the larger the decrease; but at failure the secant modulus of elasticity seems to approach a common limit of about 60 percent of its initial value.

As mentioned in the previous section, Muguruma et al. [11] observed a reduction in fatigue life of the concrete with a water-cement ratio of 26 percent is very small compared with that of concrete with a water-cement ratio of 40 percent. The moisture trapped in the microcracks or voids in concrete accelerates the propagation of microcracks which resulted in an early failure of concrete having a larger water-cement ratio (i.e., have a larger void).

In conjunction with strain and cycles measurements, Muguruma and Watanabe [20] have extended this research by incorporating acoustic emission technology to detect microcracking. In the tests, four different mixes of concrete were employed. Specimens were cured in water for 5 weeks, then removed and kept in air until subjected to fatigue loading during which time the specimens were either in air or submerged in water. Muguruma and Watanabe monitored the acoustic emissions and the maximum longitudinal strain during each cycle. The maximum longitudinal strain increased with cycles of load. They noted that when the cumulative number of emissions were plotted against the maximum longitudinal strain, the graph consisted of a linear followed by a nonlinear region, designated as "stationary fatigue process" and "rapid fatigue process", respectively, by the authors. The linear relationship ended at approximately a constant "limit" strain for a given type of concrete tested at a specific moisture condition under specific stress level.

2.5 Effect of Rest Periods

Hilsdorf and Kesler [21] were the first to investigate the effects of rest periods on the fatigue response. Plain concrete specimens, 6 by 6 in. in cross section with a water-cement ratio of 0.52 and a 28-day compressive strength of 5000 psi, were loaded in flexure. The specimens were moist cured for one week and then stored in a normal laboratory environment for 5 to 10 months until testing. The specimens were loaded in fatigue at a frequency of 450 cycles per minute with a ratio of minimum to maximum load ratio of 0.17. Each specimen was subjected to 4500 load cycles followed by a sustained constant load (rest period) equal to the lower limit of the fatigue load. The length of the rest period was either 1, 5, 10, 20, or 27 minutes. A continuous sequence of load and rest periods was applied until failure of the specimen.

The inclusion of the rest periods was found to be beneficial. No difference was found between the effect of five-minute rest periods and the effect of any longer rest periods, but the one-minute rest periods did not have as great effect as longer rest periods. It was found that the fatigue strength at ten million cycles increased from 62 to 68 percent of the ultimate static strength when rest periods were included. This increase in fatigue strength as interpreted by Neal and Kesler [22] may be caused by the healing of cracks during rest periods. The healing of cracks may be due to two phenomena—transfer of material and/or Van der Waals forces which could pull the wedge-shaped cracks together and actually shorten them.

Viswanathan [14], in a study described earlier, introduced rest periods of 9.0 and 99.0 seconds between each load application. The sustained load during the rest period was kept equal to the minimum load. Results showed no significant effect of rest periods on the fatigue strength of saturated concrete tested under submerged or moist condition. Viswanathan expected to find that fatigue strength of saturated concrete would be reduced when rest periods were introduced between the load cycles because of the recharge of pore water during rest period. The author attributed this unexpected result to the shortness of the rest periods used.

2.6 Acoustic Emission Monitoring

2.6.1 General

Acoustic emission (AE) testing is a powerful method for examining the behavior of materials deforming under stress. An acoustic emission may be defined as a transient elastic wave generated by the rapid release of energy within a material. When elastic waves are internally generated, they usually bear fundamental relationships to the imposed stress level. The monitoring of these stress waves is accomplished by using an electromechanical transducer which converts the mechanical waves into an electrical signal. As these AE are indicators of increasing stress levels in a structure, they can be used to determine nondestructively the degree of damage a structure has suffered.

The initial studies of AE phenomena which were reported in the early 1940s, dealt with the problems of predicting rockbursts in mines generated during the excavation process. The first significant investigation of AE applied to metals was by Kaiser [24] in the early 1950s. Among his observations, Kaiser noted an "absence of detectable acoustic emission at a fixed sensitivity level, until previously applied stress levels are exceeded"; this phenomenon has since become known as the Kaiser effect.

2.6.2 Acoustic Emission in Concrete

The first study of AE from concrete under stress has been conducted by Rüsh [25] in 1959. He noted that during cycles of loading and unloading below about 70 to 85 percent of the ultimate load, acoustic emissions were produced only when the previous maximum load was reached (i.e., the Kaiser effect). A year later L'Hermite [26] also measured AE from concrete; he found that a sharp increase in AE coincided with the load level at which Poisson's ratio began to increase.

Green [27], in the early 1970s, was the first to show clearly that AE from concrete is related to failure process within the material. Using a source location technique, he was able to determine the location of defects. Nevertheless, even after this pioneering work, progress in applying AE techniques in the field of concrete remains slow. A search of the available literature was done by Mindess [28] in 1988; he found only approximately 90 papers dealing with AE from concrete over about the previous 10 years. In fact, there are no standard test methods which have even been suggested on the application of AE in the field of concrete.

2.7 Summary

After examining the available literature on concrete subjected to fatigue loading, it is evident that effects of pore pressure on fatigue strength of concrete are more pronounced in the case of saturated specimens subjected to cyclic loading compared to dry specimens under the same load condition. The high pore pressure developed repeatedly during fatigue loading could promote microcracking in the concrete in a shorter period compared to dry concrete. The main conclusion that can be drawn from these studies is that the fatigue strength of submerged, unjacketed concrete is lower than that of dry concrete. Waagard et al. [15] concluded from some studies done on ND and LWA concretes that the fatigue properties of high strength LWA concrete are at least as good as those of ND concrete of similar strength. A very limited number of studies have been done on the effect of rest periods on the fatigue behavior of concrete tested under water. It is still unclear whether rest periods are beneficial or detrimental to the concrete.

CHAPTER III

EXPERIMENTAL PROGRAM

3.1 Introduction

This study considered the compressive fatigue response of concrete tested in a submerged condition, with and without hydrostatic pressure. The principal objective was to investigate the influence of rest periods interspersed between blocks of fatigue cycles. The study concentrated on the behavior of high strength LWA concrete. A limited number of tests of ND concrete were conducted for comparison. Specimens used in this study consisted of cores with 3.75-in. diameter made from a high strength LWA concrete and 5.75-in. diameter made from a normal density (ND) concrete. All specimens were roughly 12 in. high.

3.2 Specimen Preparation

3.2.1 High Strength LWA Concrete

The materials used for the preparation of the high strength LWA concrete were provided by the Norwegian Contractors. The cement was roughly equivalent to an ASTM type II cement, the properties of the portland cement are given in Table 1. The coarse aggregate was "Liapor," an expanded clay aggregate supplied in two sizes: 4 to 8 mm and 8 to 12 mm (0.16 to 0.32 in. and 0.32 to 0.63 in.). The fine aggregate was a natural sand with a bulk specific gravity (SSD) of 2.68, a fineness modulus of 3.17 and an absorption of 0.6 percent. The concrete mix proportions by weight were 1.00:1.69:0.75:0.94 of cement, fine aggregate, and smaller size and larger size coarse aggregate, respectively. The mix contained a quantity of silica fume equal to 3.9 percent of the weight of the cement as well as air entraining and high range,

TABLE 1

PORTLAND CEMENT PROPERTIES

Oxide/Compound Analysis, %	
SiO_2	22.7
Al_2O_3	3.7
Fe_2O_3	2.8
CaO	64.1
MgO	1.6
SO_3	2.7
C_3S	51.4
C_2S	26.4
C_3A	6.1
C_4AF	8.4
Available Alkalies, %	
Na_2O	0.20
K_2O	0.57
Na_2O Equivalent	0.58
Fineness, m^2/kg	388
Mortar Strength, psi	
1 day	2570
3 days	3830
7 days	4860
28 days	6490

water-reducing admixtures. The concrete mix had a water/(cement plus condensed silica fume) ratio equal to 0.43; however, the coarse aggregate which was batched dry, absorbed significant amount of water making the water/cement ratio indefinite. To approximate the amount of water absorbed by the coarse aggregate, a small quantity of aggregate was immersed in water and its water intake was monitored with time. The results of the absorption test are shown in Figure 1 which shows a substantial water intake by the aggregate.

The concrete which was cast from a single batch was mixed in a pan mixer with a capacity of 1.5 yd^3 (1.1 m^3). The dry materials were mixed continuously for 1 minute; then 95 percent of the water was added and mixed for 15 more seconds. The remaining water and admixtures were added and the concrete was mixed for 2 additional minutes. The concrete appeared to have an initial slump of roughly 7 to 9.5 in.

After the concrete was mixed, it was transported to a casting yard approximately 0.25 mi (0.4 Km) from the batch plant where it was. The concrete was then casted into a 1- by 5- by 7-ft (0.31- by 1.52- by 2.14-m) slab. The slab was cast in two lifts and consolidated with an external vibrator attached to the casting bed. The slab was then cured under plastic for 24 hrs before transporting to the Civil Engineering Laboratory where it was cured under wet burlap and plastic until coring of specimens was completed.

A standard core drill with either a 6- or 4-in. bit was used to remove cores from the slab which produced cores with 5.75 or 3.75 in. (146 or 95 mm). Cores were not taken closer than 1 in. (25 mm) to the formed surface. Only 3.75-in. diameter cores were used in this study.

Ends of the cores were prepared by first removing major surface irregularities with a brick saw. The ends of the cores were then ground smooth with a surface grinder equipped with a diamond wheel. Specimens were then stored in a fog room until time of testing. The average density of specimens was 120 pcf (1923 Kg/m^3).

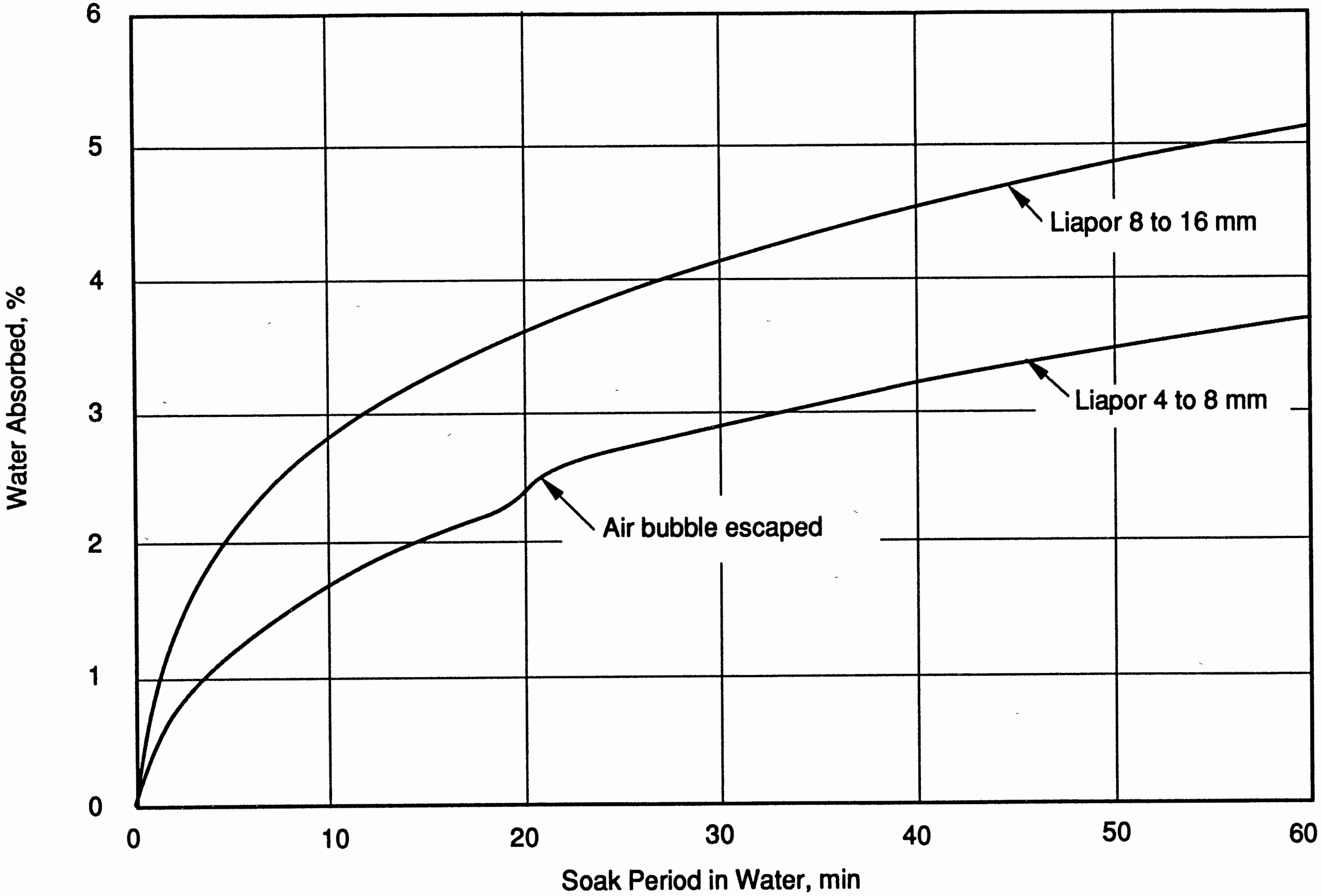


Figure 1. Water Absorption of Liapor Aggregate

Based on the average of two larger size core tests, the compressive strength at 7 days was equal to 7640 psi (52.7 Mpa) and at 28 days was equal to 8580 psi (59.2 Mpa).

3.2.2 Normal Density Concrete

The normal density concrete cores used in this study were extra specimens taken on a separate project. This project used a Class A paving mix with concrete supplied by a ready-mix plant; the concrete had a nominal water/cement ratio of 0.43 and proportions by weight equal to 1.00:1.60:2.63 of cement, fine aggregate, and coarse aggregate, respectively.

The cores were obtained from the central region of a 1- by 5- by 5-ft (0.31- by 1.52- by 1.52-m) slab which had been cast in two lifts and consolidated with an internal vibrator. The concrete had a slump of 2.5 in., an air content of 3.8 percent, and a unit weight equal to 148 pcf (2372 Kg/m^3). Cores were then prepared for the tests by sawing and grinding the end surfaces as described above. Specimens were stored in the moist room until time of testing. The compressive strength at 7 days was equal to 4690 psi (32.3 Mpa) and at 28 days was equal to 6000 psi (41.4 Mpa); these strengths were obtained from control cylinders cast in steel molds.

3.3 Test Equipment

Loads were applied by a servo-controlled material test system with a capacity of 600 kips (2700 KN). The columns, cross-head, and load cell were designed for a capacity of 1100 kips (4900 KN) which resulted in a rigid test frame. Specimens were placed inside a triaxial cell rated for a pressure of 10,000 psi (69 Mpa). The cell was equipped with a hydraulic balance feature to offset the hydrostatic pressure acting against the loading ram. A piston-style accumulator was used to separate the oil going to the balance unit from the water being delivered to the cell. Deaired water was supplied to the triaxial cell using an air-over-water pump. For specimens tested under 1000 psi (7 Mpa) confining pressure, water entering the cell during the test was monitored by a water-rated, double acting, hydraulic cylinder. A 0.5 psi rated pressure transducer was used to monitor the water intake of the concrete during the test for specimens tested submerged in water with negligible pressure in the cell. An overall schematic of the test setup is given in Figure 2.

A microcomputer was used to control the test system and acquire data. The computer initially programmed a function generator to generate the sinusoidal command voltage corresponding to desired maximum and minimum load levels; after a test was underway the computer continually monitored the actual maximum and minimum load levels and reprogrammed the function generator as necessary. Data acquisition was accomplished with a 4-channel A/D board with 12-bit resolution; all channels were sampled simultaneously. The A/D board monitored the applied load, longitudinal strain, and volume of water entering the triaxial cell. The longitudinal strain was obtained using two LVDT transducers mounted diametrically opposed on the specimen. Aluminum brackets supporting both the transformers and the core rods were glued to the specimen. For specimens tested under high pressure, an LVDT was used to monitor the volume of water entering the triaxial cell, the core rod was connected to the piston rod of the doubleacting hydraulic cylinder.

3.4 Acoustic Emission Instrumentation

The main elements of an AE detection system is shown schematically in Figure 3. A piezoelectric sensor is used to convert the surface displacements into electric signals. The output voltage from the transducer is directly proportional to the strain of the surface in contact with the specimen. A single, broadband, 100 to 1000 KHz, differential-style transducer was placed in a brass case to prevent mechanical or electrical damage from the surrounding water at high pressure. The AE data are strongly affected by sensitivity of the sensor. Any variation in sensitivity can be contributed from mounting condition, damage of the sensor, and degradation from aging and environment. At the beginning of the testing program, the sensor was calibrated to ensure its reproducibility along the testing program. A pencil lead

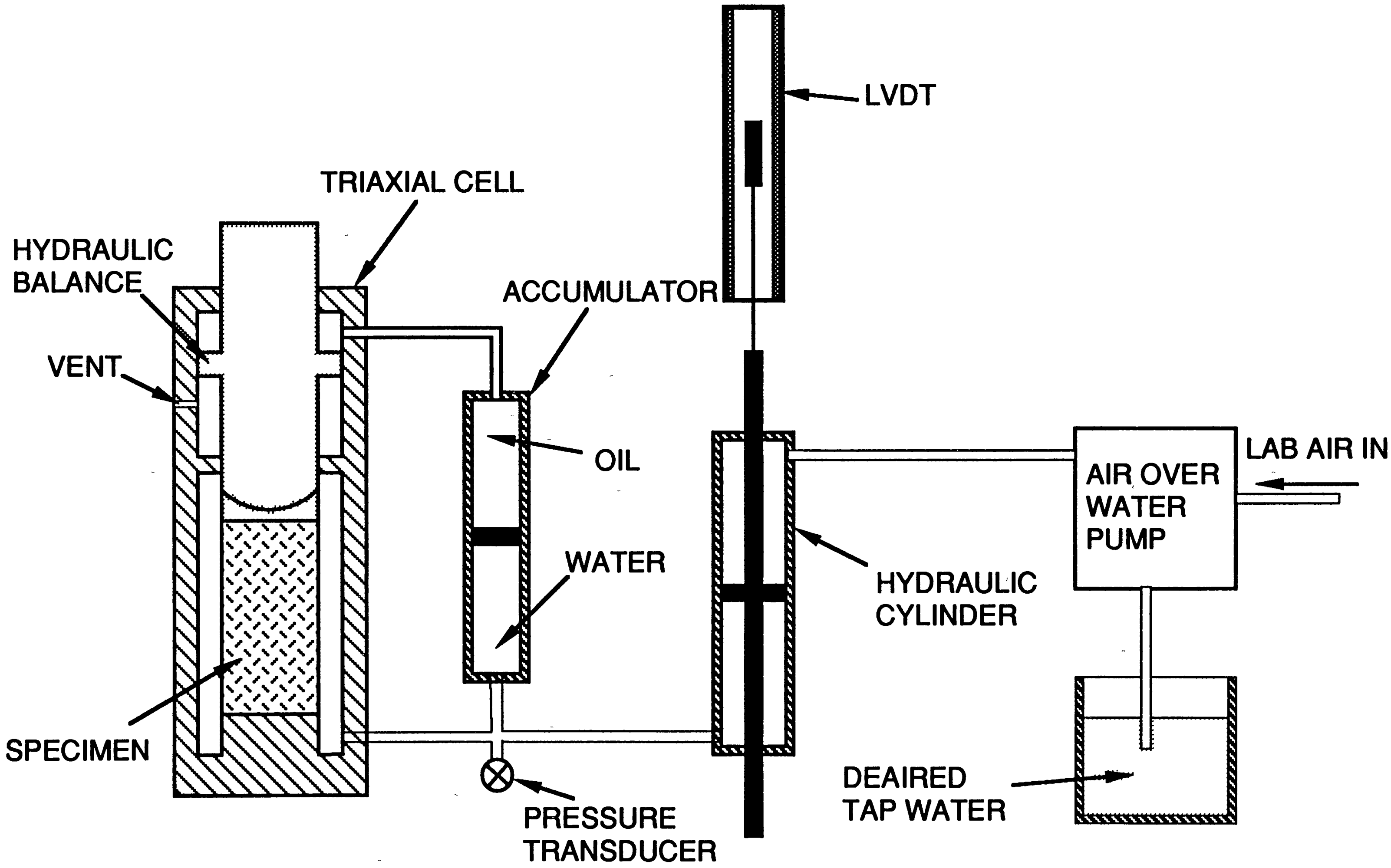


Figure 2. Schematic of Test Setup

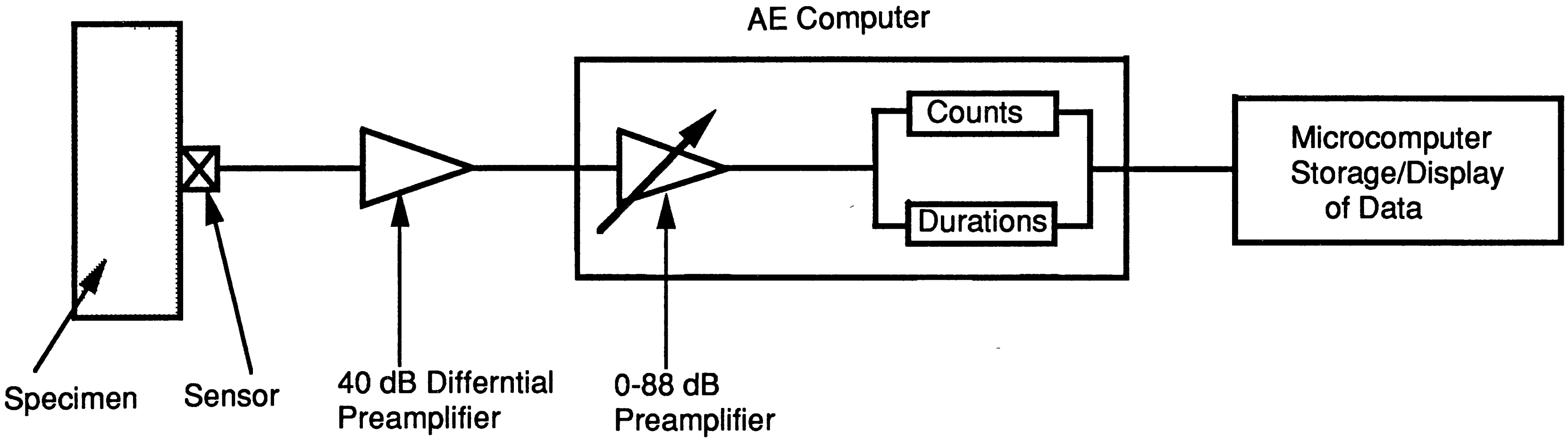


Figure 3. Diagram of Acoustic Emission Measurement System

fracture calibration method was used; a complete guideline for this method is described in ASTM E976 [29].

The transducer was attached to the surface of the specimen at mid-height with rubber tubing. At the point of attachment, the cylindrical surface was ground flat; vacuum grease was used as a couplant between the transducer and the concrete. AE sensors produce low amplitude signals; to avoid noise problems it is necessary to provide a preamplifier close to the sensor. In this study, a preamplifier with a fixed gain of 40 dB with a broadband, 20 KHz to 2 MHz, was employed. The signal from the preamplifier is sent to the AE instrumentation system. In this test program, the data acquisition was achieved in a microprocessor system featuring a multibus front end, interfaced to a microcomputer where graphical and numerical data can be displayed and/or stored for post-test analysis. A bandpass filter with a band frequency of 100 to 300 KHz is used in the AE system.

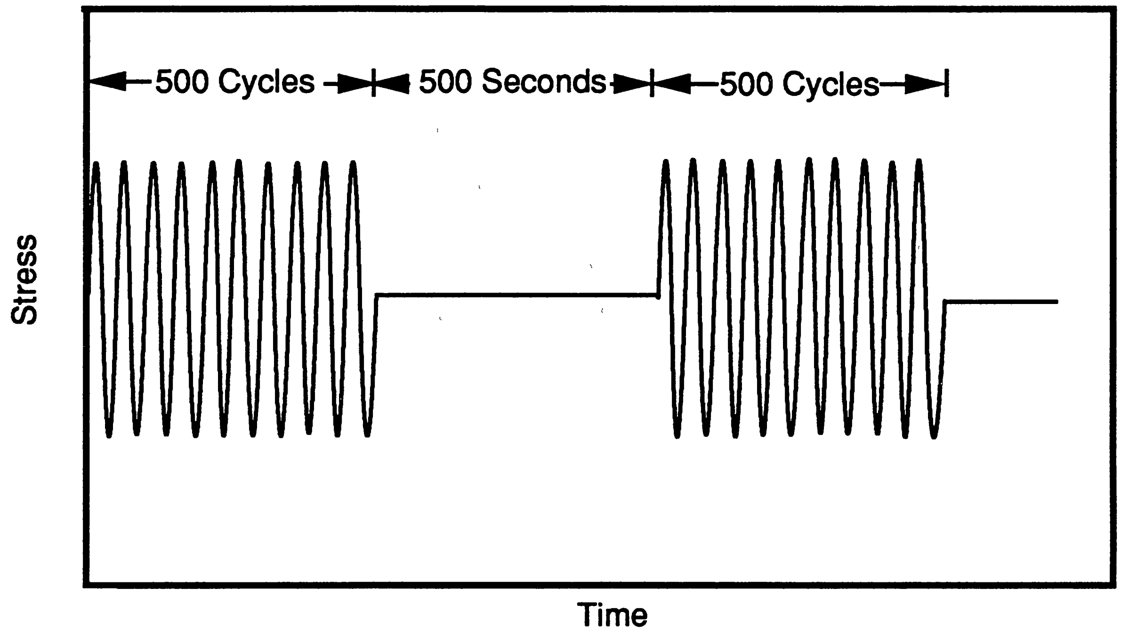
Damage is assumed when the acoustic pulse exceeds a certain arbitrary threshold level. After a series of preliminary tests in which concrete specimens—not part of the test program—were subjected to load, it was determined that a gain of 20 dB and a threshold sensitivity of 63 dB were found to be acceptable for the particular test equipment and laboratory environment.

3.5 Test Program

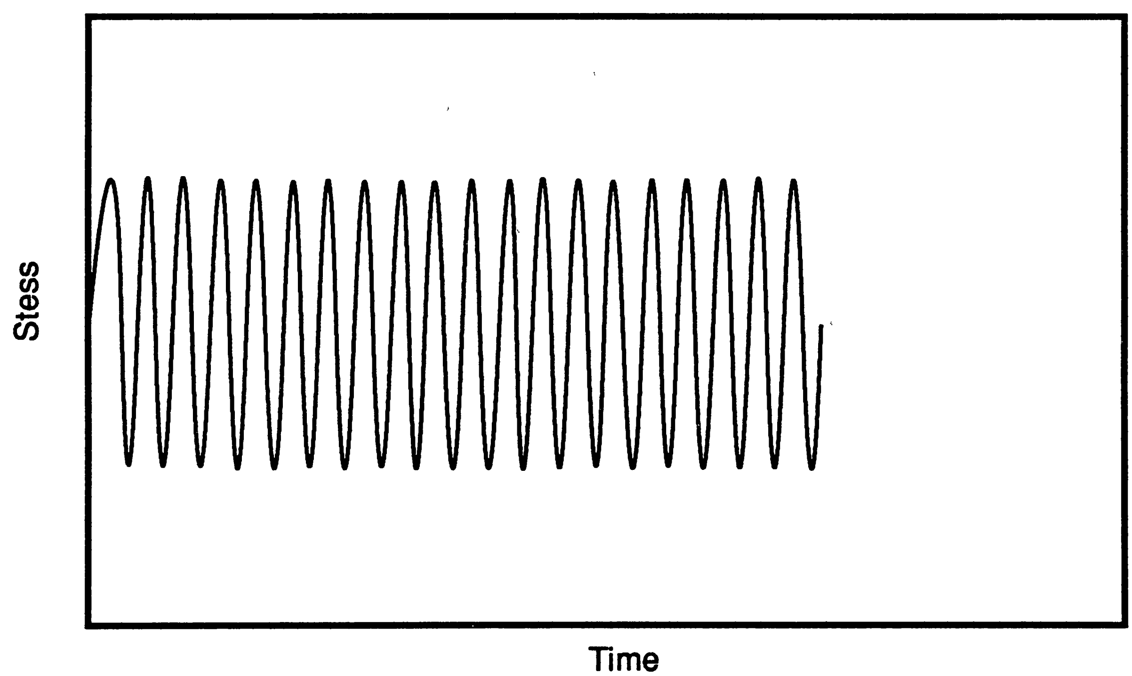
All concrete used in this study was continuously cured in a moist room. The minimum age for the high strength LWA concrete was 1156 days and 472 days for the ND concrete. Two loading programs were employed for both types of concrete—a continuous fatigue loading until failure and fatigue loading interrupted by rest periods. All specimens were tested in water without jackets inside the triaxial cell with either a negligible or a 1000 psi (7 Mpa) confining pressure. All ND concrete specimens were tested under the 1000 psi (7 Mpa) water pressure.

In both loading programs, the maximum stress level was 70 percent of the static compressive strength. This strength was the average of two moist cores loaded at a rate of 250 Kpa/s in air. The minimum stress level was 5 percent of the maximum stress level. Sinusoidal loading was applied at a frequency of 1 Hz. The load program with and without rest periods is shown in Figure 4. During the rest period, the specimen was subjected to a constant load equal to the mean of the maximum and the minimum fatigue loads. A continuous sequence of load and rest period was applied until the specimen failed.

In exploratory tests, one core was placed in the triaxial cell and subjected to a hydrostatic pressure of 7 Mpa. A small uptake of water was observed. Based on this observation, before the initiation of tests, one- and two-hour soak periods were observed after the application of confining pressure for ND high strength and LWA concrete, respectively. No soak period was employed for cores tested submerged without a confining pressure.



(a) Fatigue Load Interspersed With Rest Periods



(b) Continuous Fatigue load

Figure 4. Load Configurations

CHAPTER IV

EXPERIMENTAL RESULTS

The cycles to failure data are provided in Table 2. In this table, the number following the type of concrete indicates the order of test. The quantities of water entering the triaxial cell during both fatigue loading and rest periods are shown in Figures A.1 through A.5 in the Appendix. In these figures, the cumulative quantity of water entering the triaxial cell is expressed as a percentage of the volume of sample. For specimens tested under continuous fatigue loading, data were sampled according to the following formula:

$$\text{Sample Cycle} = \text{Integer}\ (10^{0.2n})$$

where n = 1, 2, 3 , ... etc.

Consequently, the maximum water uptake shown in these figures omits water entering the triaxial cell between the time of the last measurement and the time of failure. Therefore, the last points shown in these graphs are not the total water uptake at the time of failure. A different data acquisition program was used for specimens that included rest periods where data were collected at cycles 1, 20, 50, 100, 250, and 500 in each load block. Consequently, for tests involving rest periods, water uptake was always measured within a couple of hundred cycles of failure, while the last water measurement for continuous loading could be several thousands of cycles prior to failure. From these figures, one specimen for each test condition was selected and plotted individually. These results are shown in Figures 5 through 11. In conjunction with water uptake measurements during both loading and rest periods, cumulative acoustic emission counts were acquired during the testing period and shown in these figures.

TABLE 2

TEST RESULTS

Core	Rest Periods (Yes/No)	Confining Pressure (MPa)	Cycles to Failure	Mean Fatigue Life
LWA 2	No	7.0	111561	
LWA 5	No	7.0	88009	
LWA 6	No	7.0	131752	110440
LWA 1	Yes	7.0	24070	
LWA 3	Yes	7.0	5575	
LWA 4	Yes	7.0	48400	
LWA 7	Yes	7.0	4542	20647
LWA 8	No	0.0	4071	
LWA 9	No	0.0	12251	8161
LWA 10	Yes	0.0	5323	
LWA 11	Yes	0.0	2996	
LWA 12	Yes	0.0	2025	
LWA 13	Yes	0.0	12068	5603
ND 1	No	7.0	3719	
ND 4	No	7.0	19472	
ND 6	No	7.0	16851	13347
ND 2	Yes	7.0	7650	
ND 3	Yes	7.0	4263	
ND 5	Yes	7.0	11153	7689

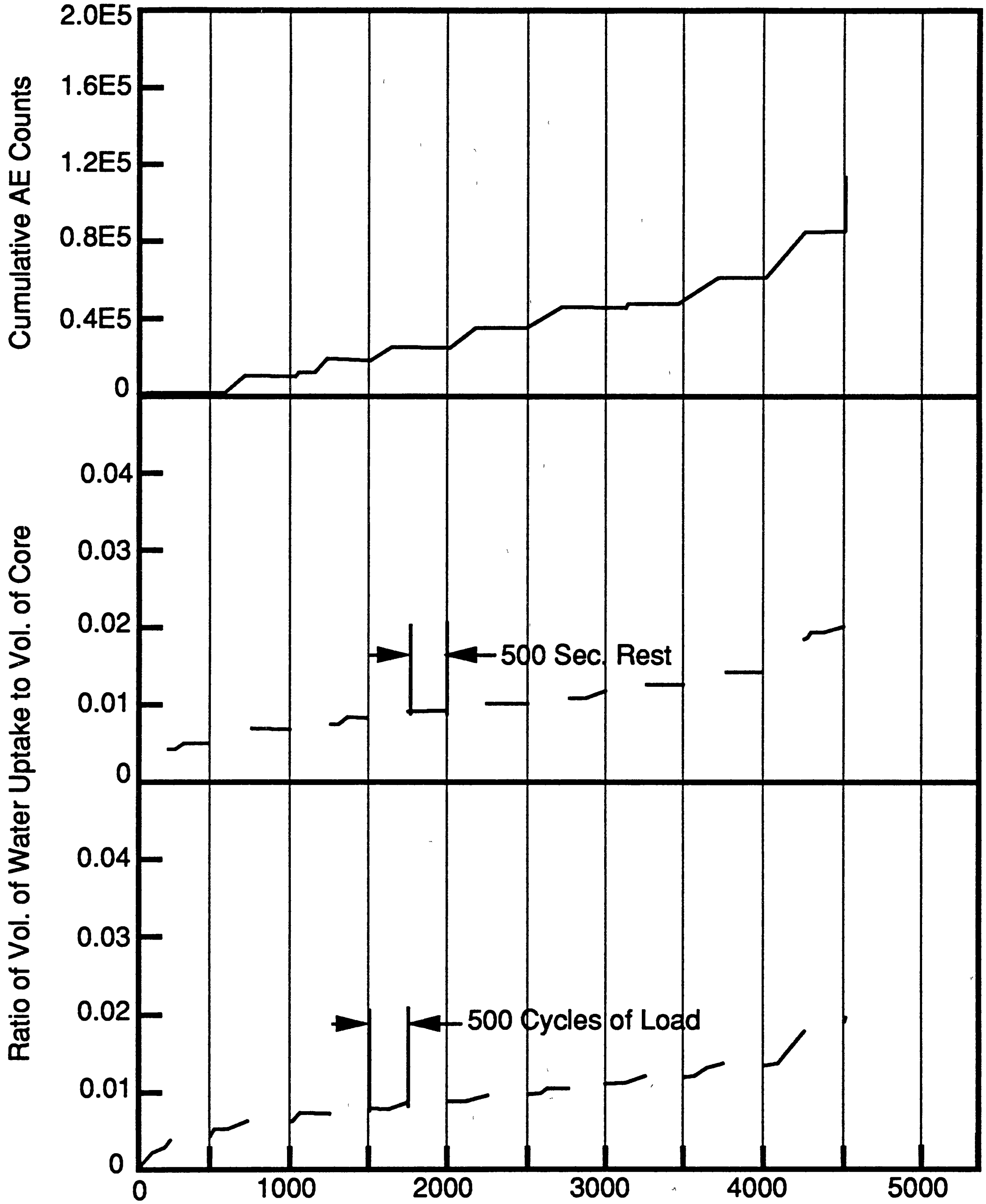


Figure 5. AE and Water Uptake Data for Core LWA 7 (P = 7 Mpa)

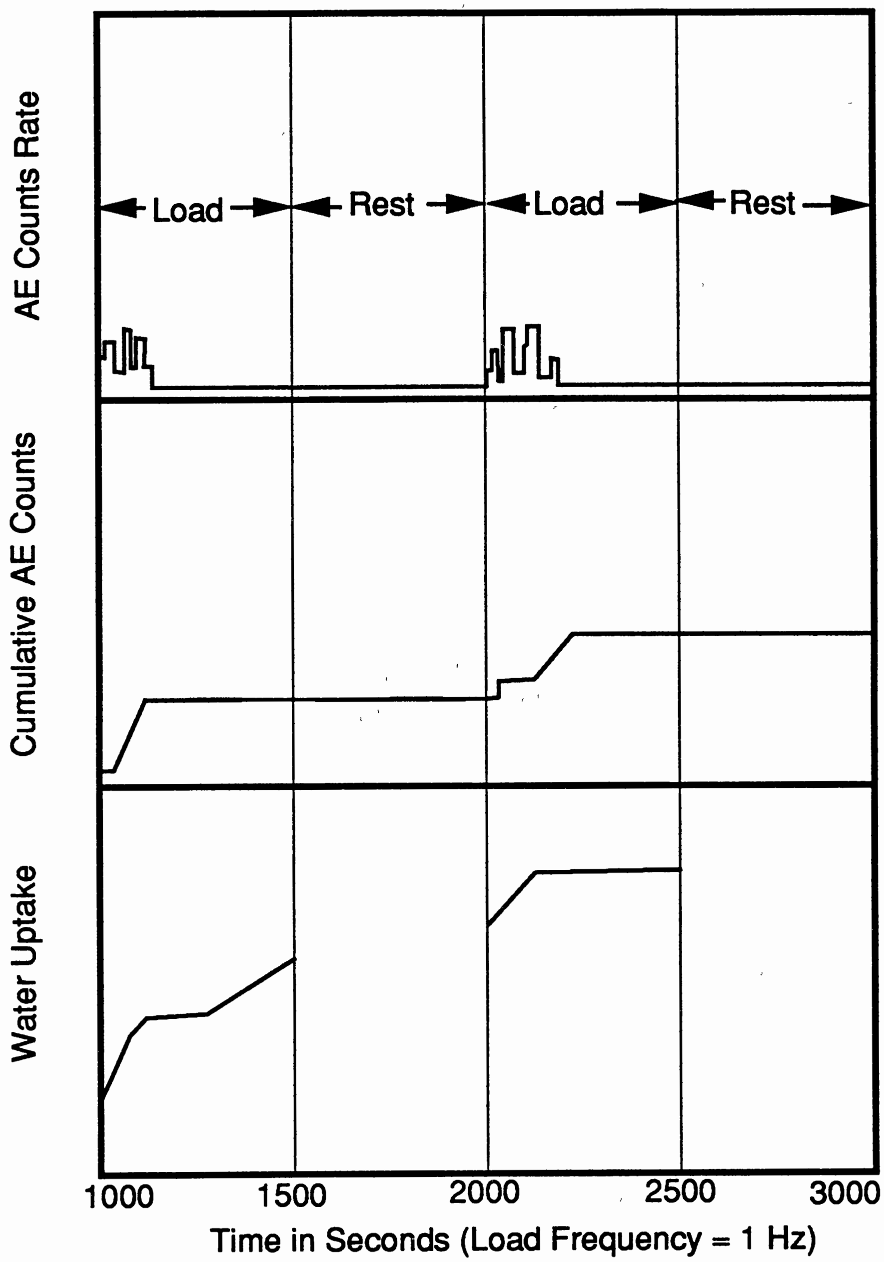


Figure 6. Effect of Rest Periods on Concrete

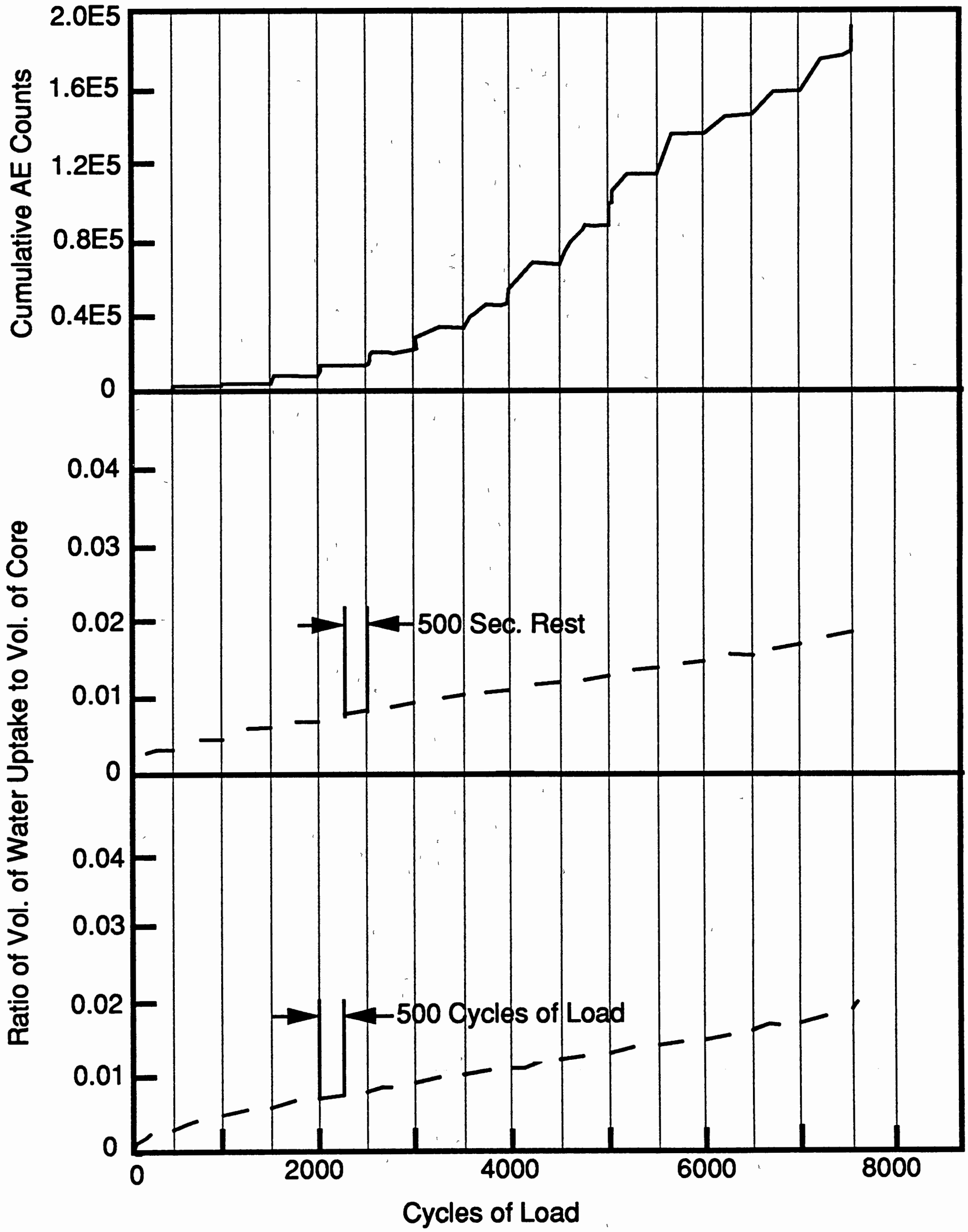


Figure 7. AE and Water Uptake Data for Core ND 2 (P = 7 Mpa)

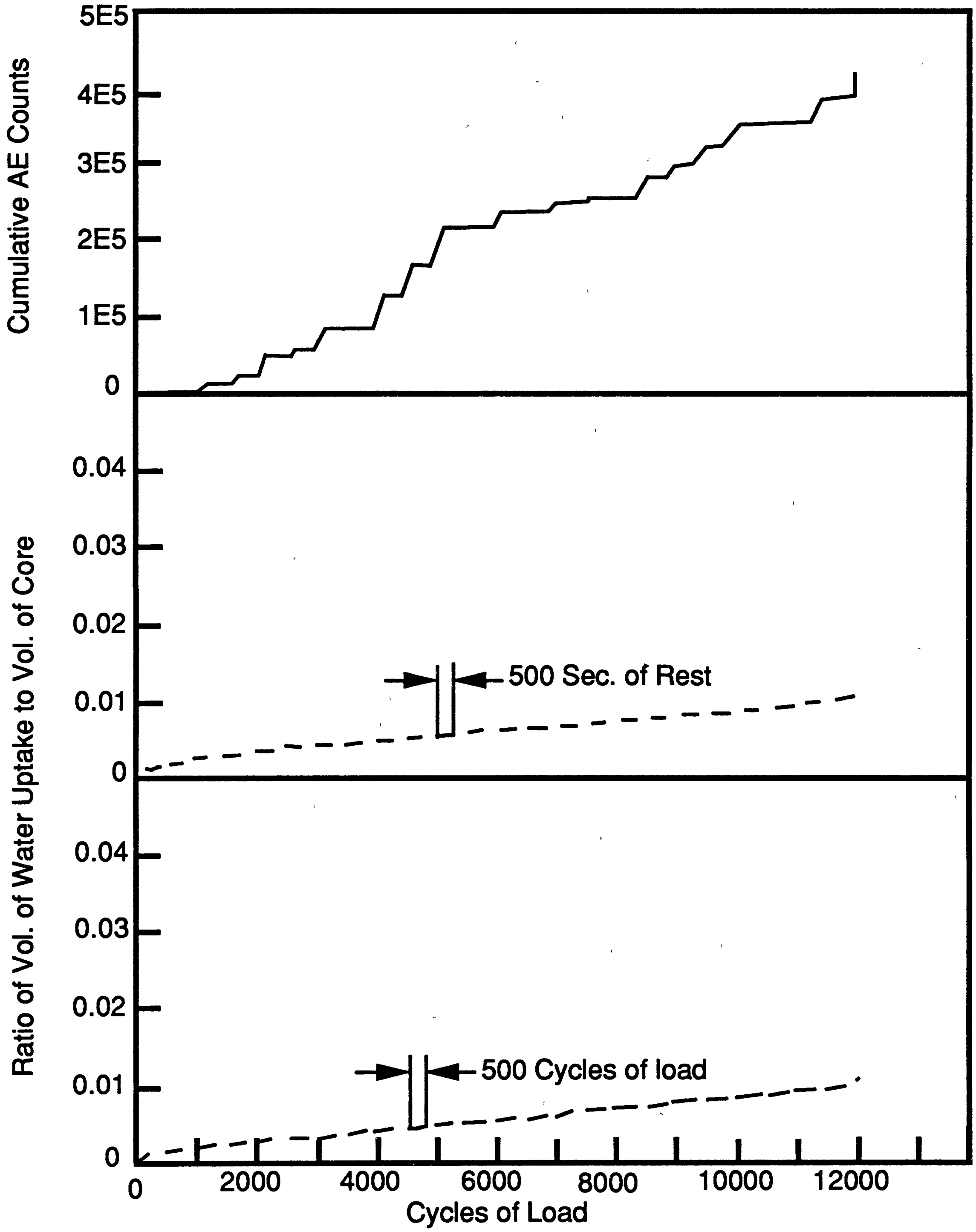


Figure 8. AE and Water Uptake Data for Core LWA 13 (P = 0 Mpa)

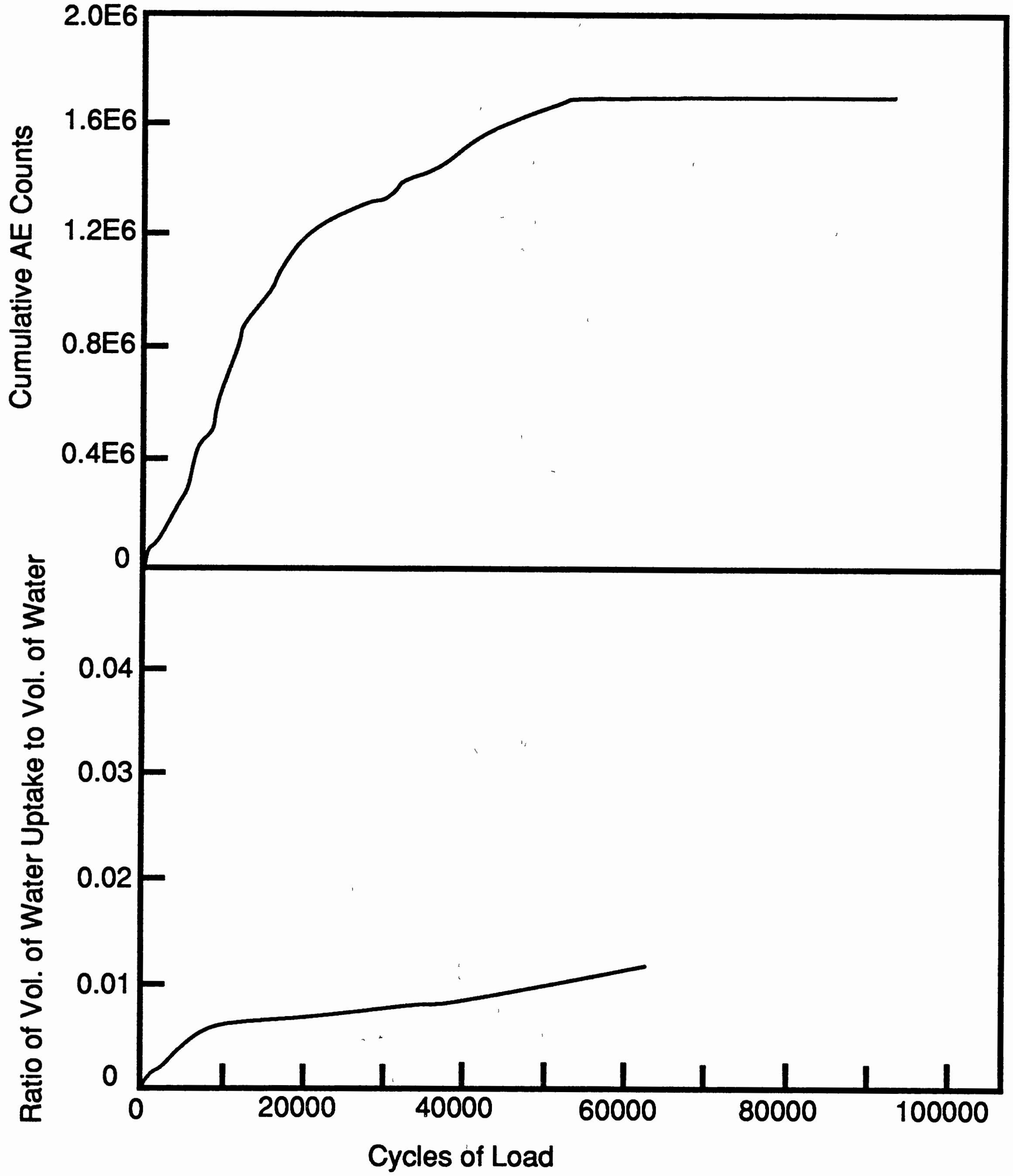


Figure 9. AE and Water Uptake Data for Core LWA 5 (P = 7 Mpa)

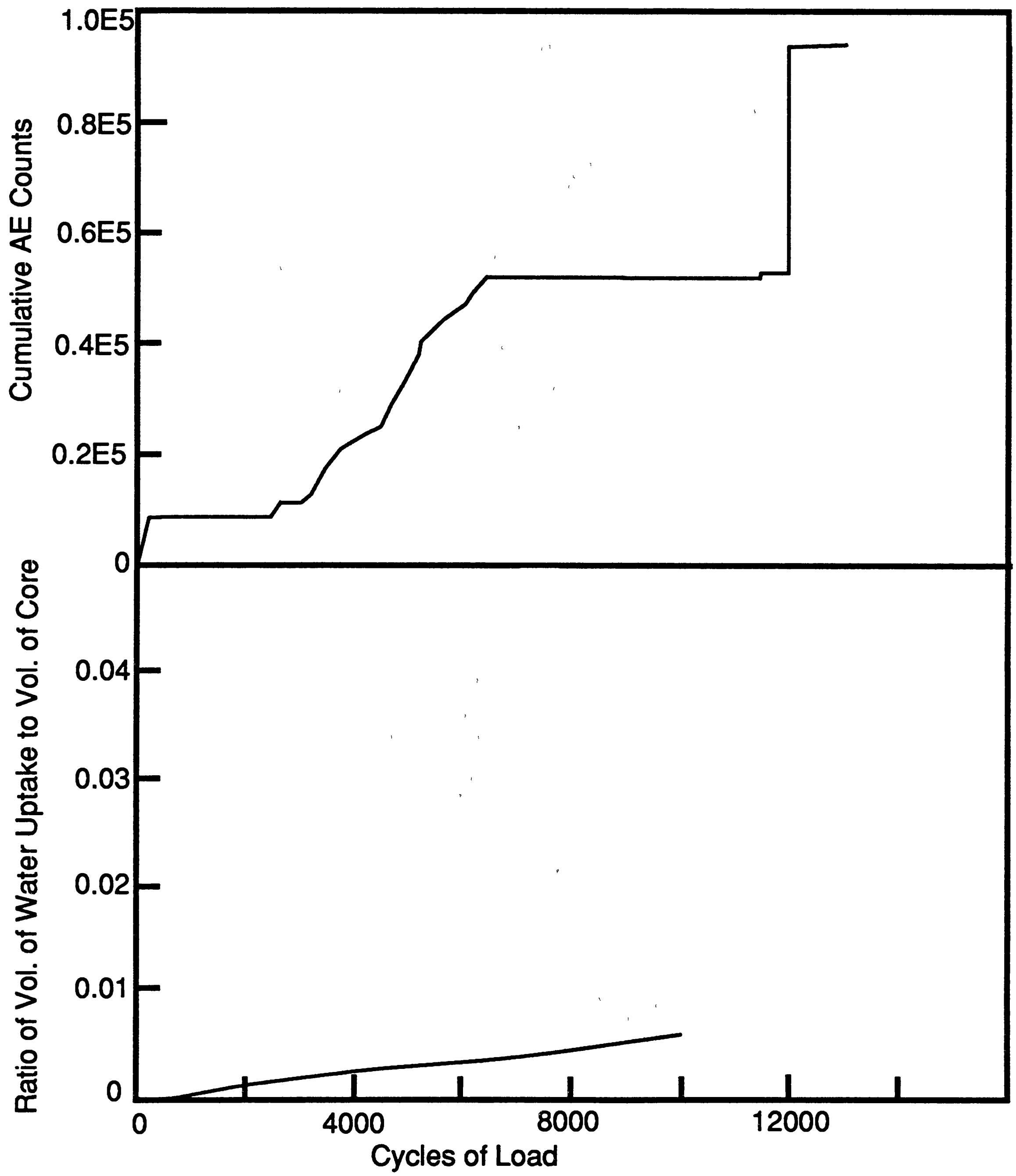


Figure 10. AE and Water Uptake Data for Core LWA 9 (P = 0 Mpa)

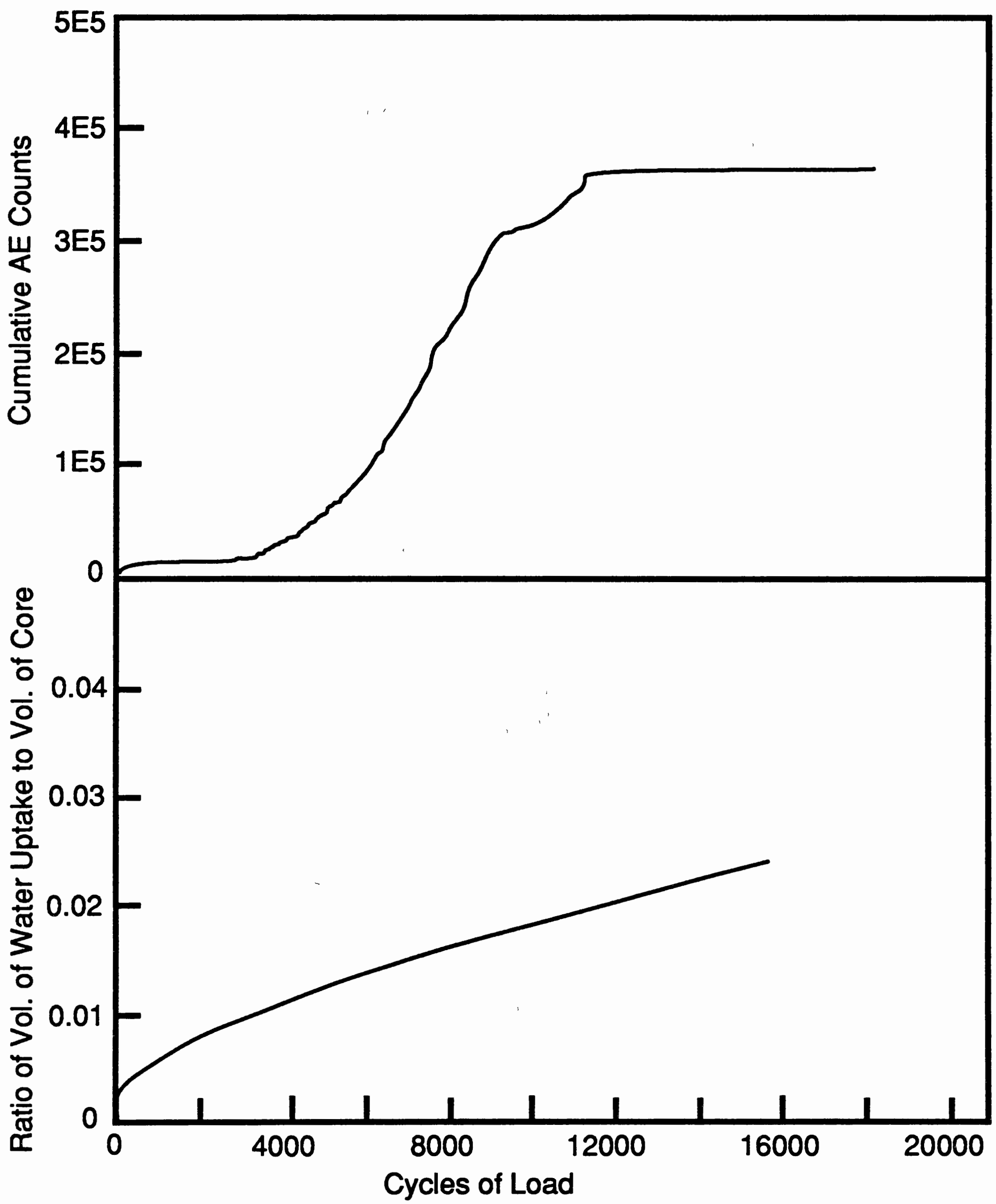


Figure 11. AE and Water Uptake Data for Core ND 4 (P = 7 Mpa)

Before the initiation of tests under high pressure, specimens were exposed to a 7 MPa water pressure for either one or two hours, depending on the permeability of concrete being tested. The two-hour soak period was employed for the high strength LWA concrete. It is impossible to reach global saturation of concrete in such a short period of time, especially for LWA concrete. The quantity of water absorbed by concrete during a test was estimated by extrapolating soak-period data to the maximum time involved with fatigue tests and was found to be negligible compared to the amount of water absorbed by concrete due to cracking.

CHAPTER V

ANALYSIS AND DISCUSSION OF RESULTS

5.1 Fatigue Strength

The results of fatigue strength are presented in the form of an S-N diagram in Figures 12 and 13 for high strength LWA and ND concrete, respectively. It can be seen from these figures that specimens made of high strength LWA concrete tested under continuous fatigue load with a 7 MPa confining water pressure exhibited the longest fatigue lives. Table 2 shows the mean fatigue lives of specimens tested under fatigue load interspersed with rest periods are lower than those tested under continuous fatigue load for the same type of concrete and moisture condition. For example, reduction in the mean fatigue lives of concrete going from continuous fatigue loading to fatigue loading interspersed with rest periods is as follows:

1. 80 percent reduction for high strength LWA concrete tested with a 7 MPa confining pressure,
2. 30 percent reduction for high strength LWA concrete tested with a 0 MPa confining pressure, and
3. 40 percent reduction for ND concrete tested with a 7 MPa confining pressure.

The high strength LWA concrete is the most effected by rest periods when tested with 7 MPa confining pressure. Figure A.1 shows the water uptake of high strength LWA concrete during both test programs. In the case of specimens tested under fatigue load interspersed with rest periods, the water uptake consists of three different stages: a high water uptake from 0 to about 10 percent of total fatigue life, a uniform uptake from 10 to about 90 percent, and a high uptake until failure. No such conclusion can be drawn from specimens tested under continuous fatigue load since

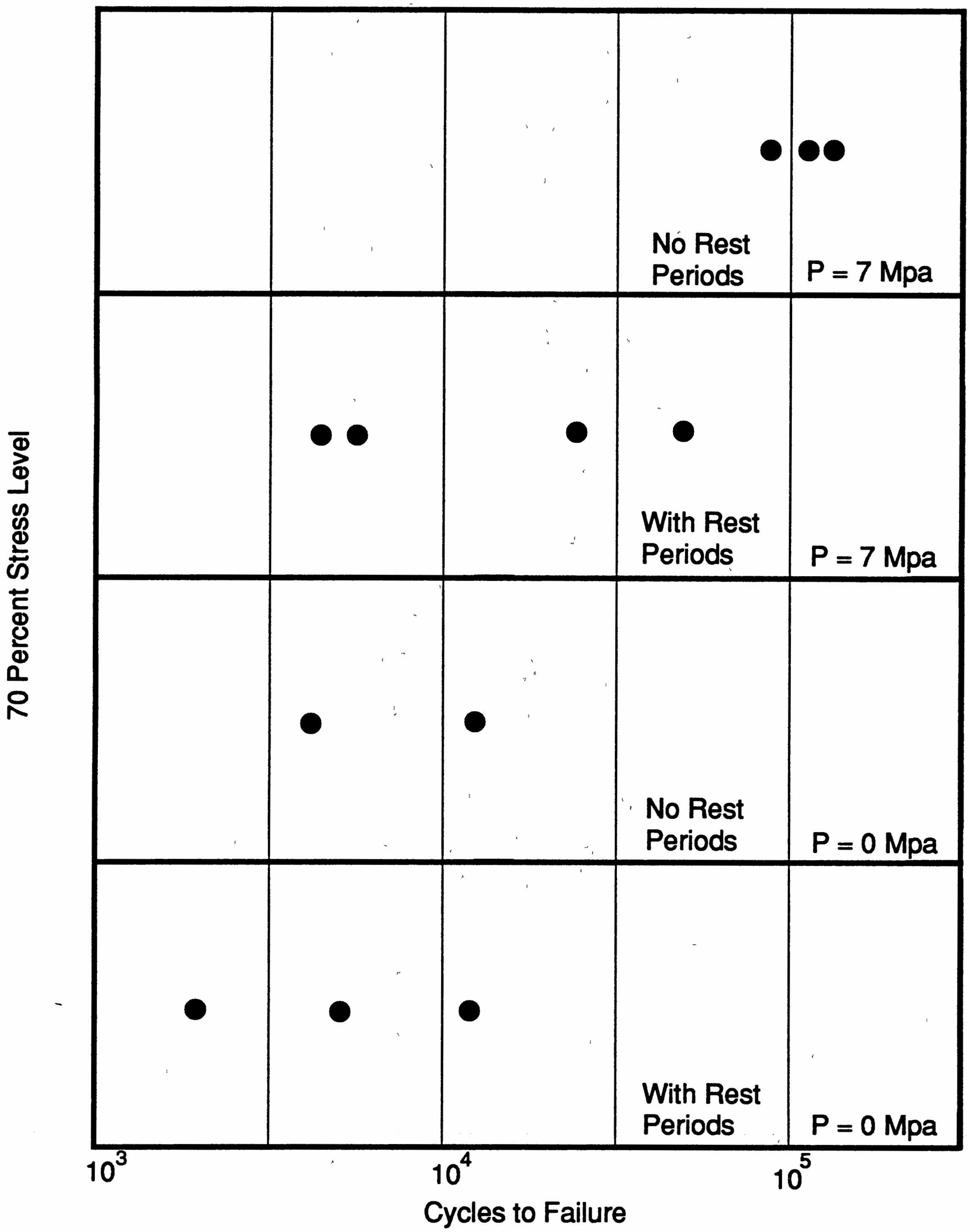


Figure 12. S-N Diagram for High Strength LWA concrete

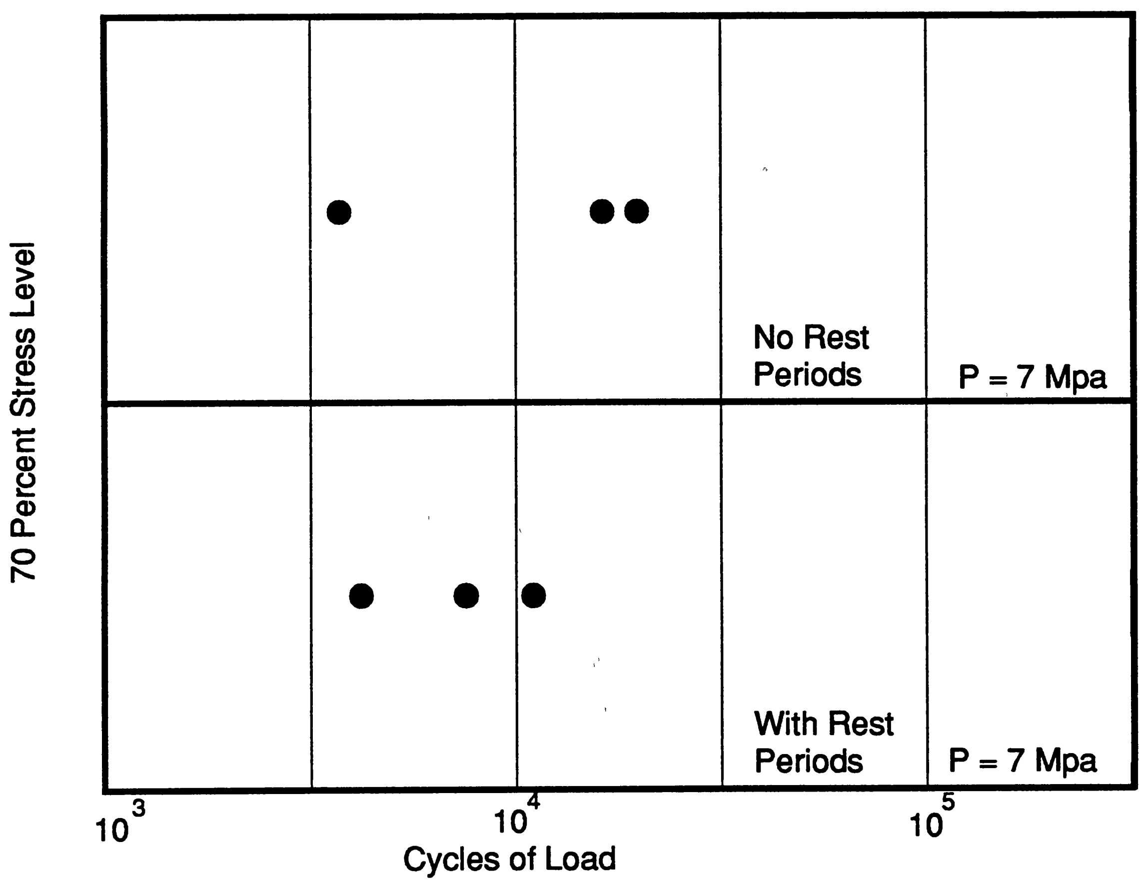


Figure 13. S-N Diagram for ND Concrete

no data were collected near failure. A closer look at the water uptake and acoustic emission data reveals that most of the damage represented by water entering the specimen or cumulative acoustic emission counts occurs in the first 200 to 300 cycles of a load block following a rest period. This phenomenon is illustrated in Figures 5 and 6. Figure 6 shows two loading blocks from Figure 5 for clarity. If a rest period was introduced after each cycle of load, the fatigue strength of concrete would be much lower.

5.2 Stress-Strain Characteristics

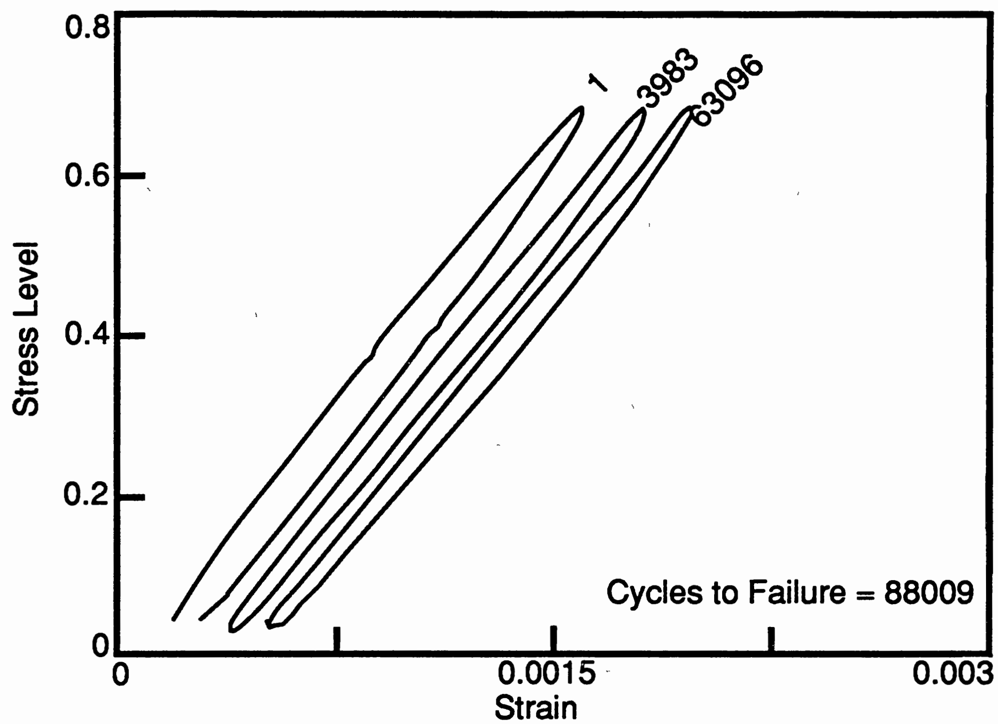
Stress versus strain diagrams are shown in Figures 14 through 16. In these figures three cycles were plotted per test condition. Generally, it can be said the strain at any stress level gradually increases with increased number of cycles. From these figures, the increase in strain and shape of the curves varies, depending on the type of concrete, the test moisture condition and the type fatigue loading (with or without rest periods).

5.2.1 Type of Concrete

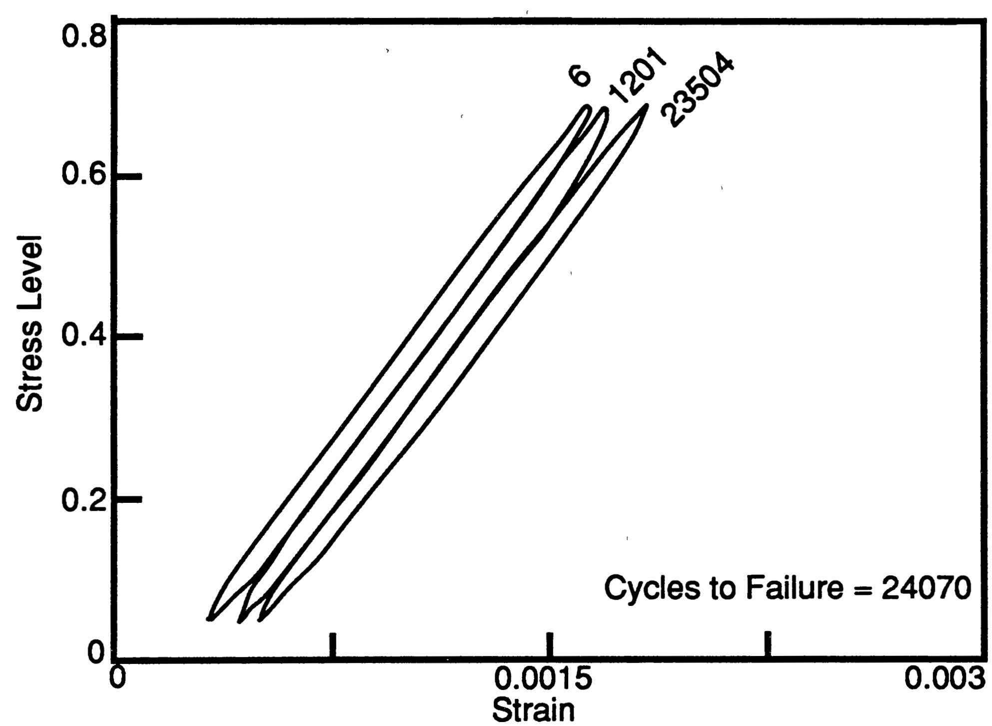
The stress-strain diagram curve varies with the number of load repetitions. In the case of ND concrete, the curve (loading segment) changes from a concave form toward the strain axis to a straight line and further to a convex form as illustrated in Figure 16. The degree of convexity is an indication of how near the concrete is to failure. However, in the case of high strength LWA concrete, the curve remains almost unchanged during a test. This phenomenon may be related to the importance of bond deterioration in the fatigue life of ND concrete.

5.2.2 Confining Pressure

A noticeable difference in the shape of the stress-strain diagrams for specimens tested under a 7 or 0 MPa confining water pressure is observed. This phenomenon is shown in Figures 13 and 14. The area enclosed by the stress-strain hysteresis—the sum of both elastic and inelastic energy—is larger in the case of concrete tested

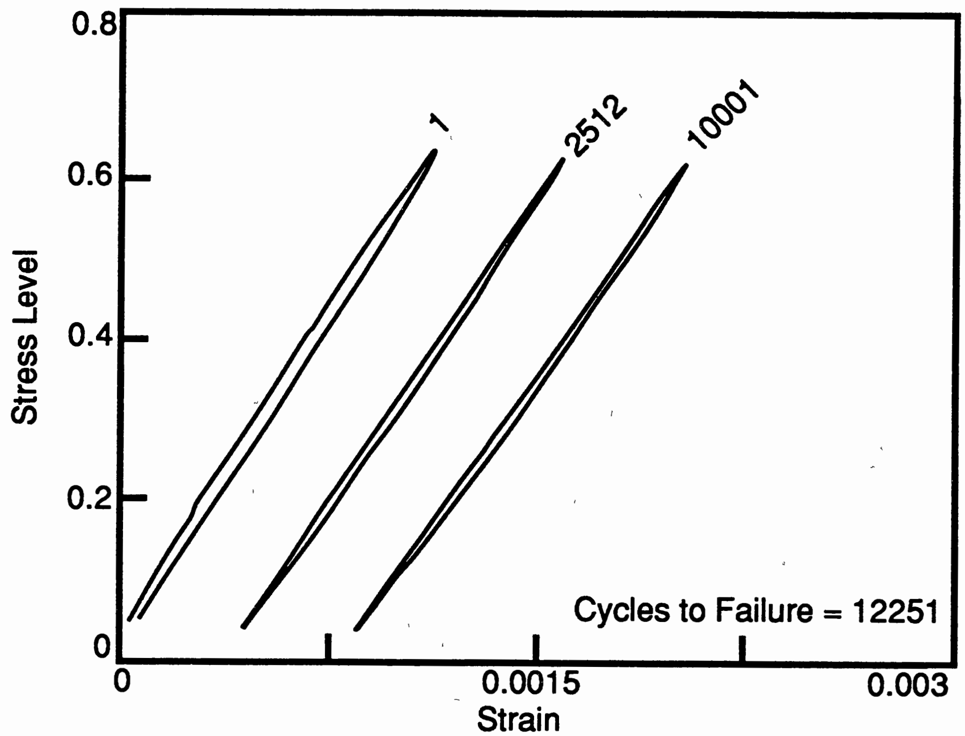


(a) LWA Concrete; Without Rest Periods

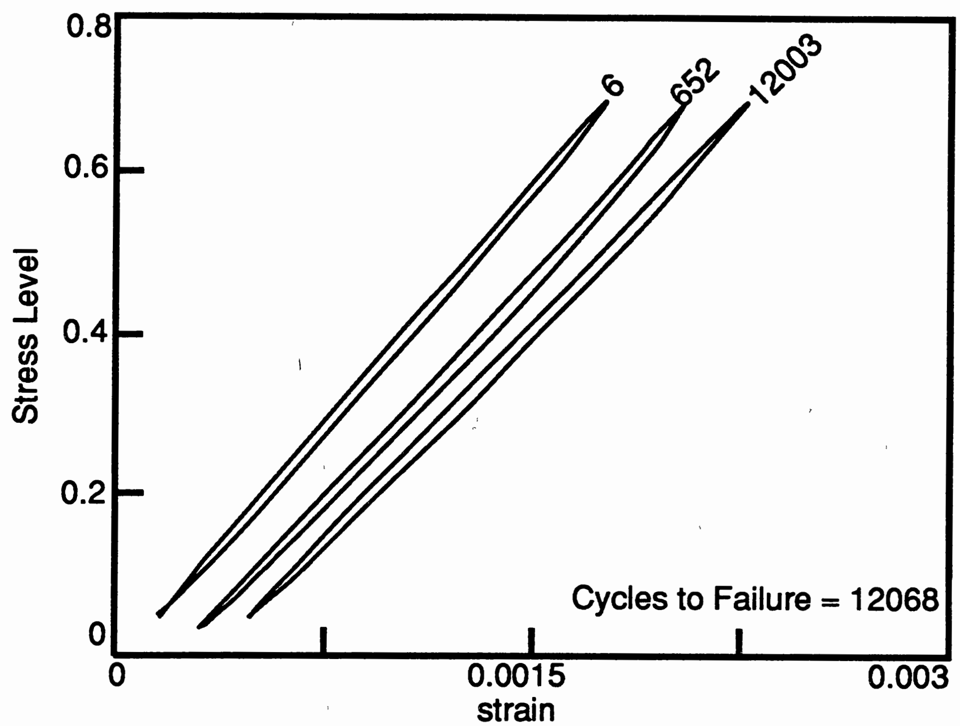


(b) LWA Concrete; With Rest Periods

Figure 14. Stress-Strain Diagram for LWA Concrete (P = 7 Mpa)

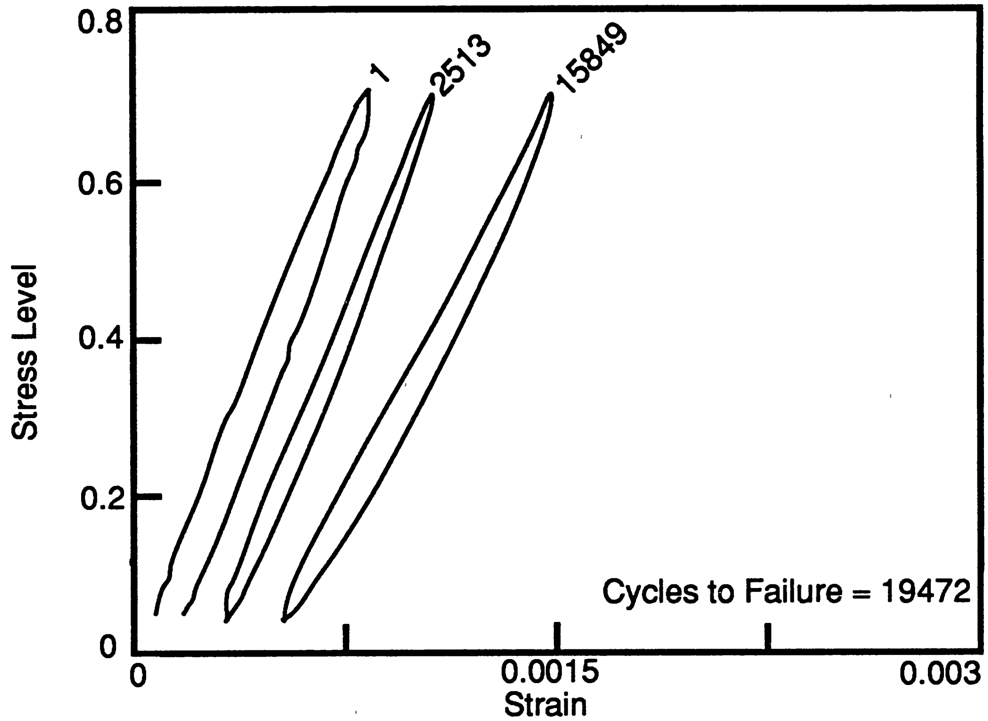


(a) LWA Concrete; Without Rest Periods

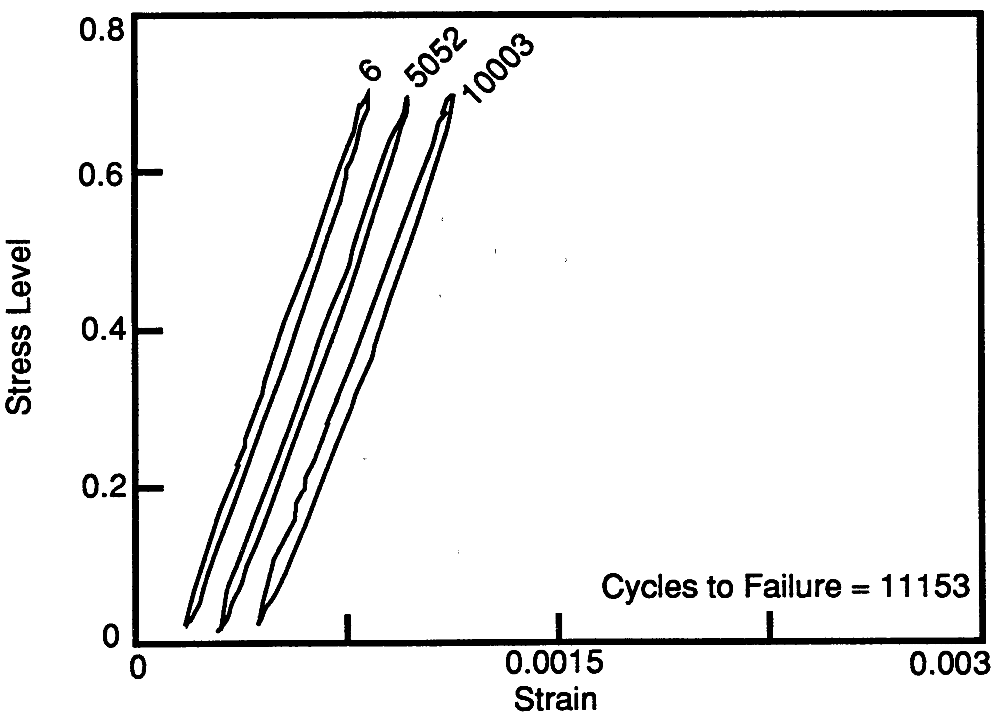


(b) LWA Concrete; With Rest Periods

Figure 15. Stress-Strain Diagram for LWA Concrete (P = 0 Mpa)



(a) ND Concrete; Without Rest Periods



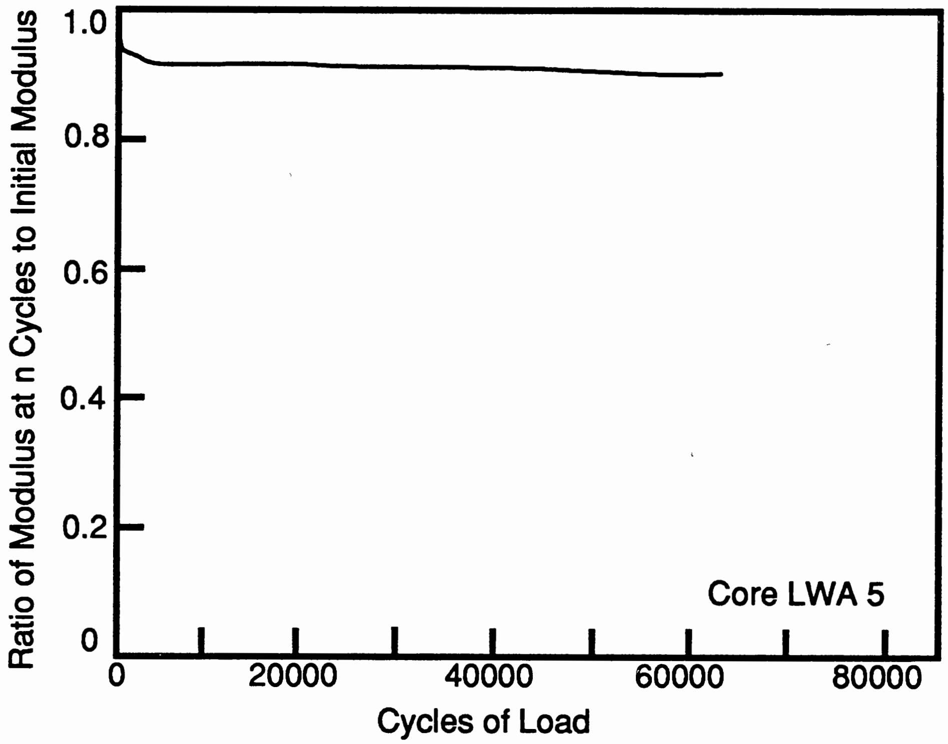
(b) ND Concrete; With Rest Periods

Figure 16. Stress-Strain Diagram for ND Concrete (P = 7 Mpa)

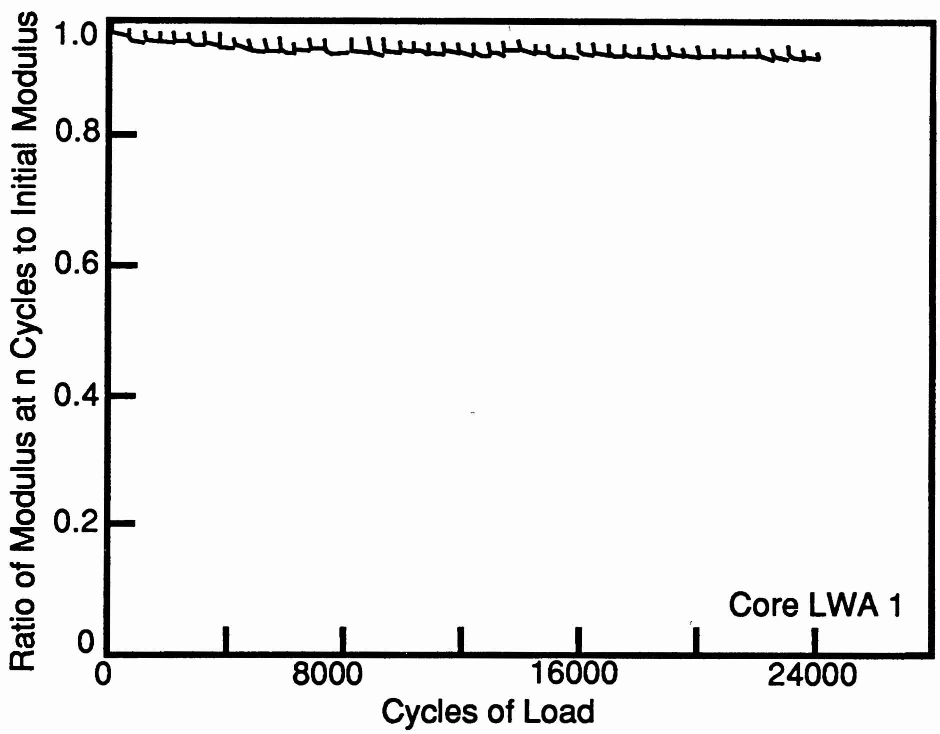
under 7 MPa confining pressure. This difference in area is probably related to the shape of the unloading segment of the stress-strain diagram. Water has a greater opportunity to reach some of the formed cracks and fill them when it is under high pressure. Therefore, a crack (parallel to the load) full of water may prevent the concrete from regaining some of its deformation during unloading and hence result in a permanent strain during a cycle.

5.2.3 Rest Periods

It can be seen that stress-strain hystereses are less spaced when concrete is tested under fatigue load interspersed with rest periods compared to that tested under continuous fatigue load. This phenomenon is observed for both concretes tested with either 0 or 7 MPa confining pressure. Water has a greater opportunity to reach zones where fracture is occurring and continue to fill voids near the surface during rest periods. Therefore, concrete gains some of its axial stiffness during rest periods. Sustained loading also had a strengthening effect on concrete, probably because of the consolidation of the hardened cement paste. This hypothesis is supported by data shown in Figure 17. In this plot, the axial stiffness is presented in a nondimensionalized form by dividing the stiffness of a core at various number of cycles by the initial stiffness.



(a) Continuous Fatigue Loading



(b) Fatigue Loading Interspersed With Rest Periods

Figure 17. Reduction in Axial Stiffness

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

6.1 Summary and Conclusions

The purpose of this study was to investigate the influence of rest periods interspersed between blocks of fatigue cycles on concrete. Fatigue tests were performed on unjacketed concrete cores under submerged condition, with and without hydrostatic pressure. The study concentrated on the behavior of high strength LWA concrete, but a limited number of tests on ND concrete were conducted for comparison.

Specimens used in this study consisted of 3.75-in. diameter high strength LWA concrete and 5.75-in. diameter ND concrete. All tests were conducted under water with either 0 or 7 MPa confining pressure. Two loading programs were employed: a continuous fatigue loading until failure of the specimen and a combination of blocks of 500 cycles of load followed by 500-second rest periods. The maximum stress level was 70 percent of the compressive strength; the minimum stress level was 5 percent of the maximum stress level. The sustained stress during rest periods was equal to the mean of maximum and minimum stress used during fatigue load.

The results of this study can be summarized as follows:

1. Fatigue life of concrete subjected to fatigue load interrupted with rest periods was lower than that for concrete subjected to continuous fatigue load.
2. The high strength LWA concrete is much more effected by rest periods compared to ND concrete when tested in a submerged condition with 7 MPa confining pressure.

3. The reduction in fatigue strength of concrete when loads are interspersed with rest periods is more pronounced for concrete tested in a submerged condition with 7 MPa confining pressure.

6.2 Suggestions for Future Work

As indicated in the literature review, a very limited number of studies have been done in this area, and no major results have been found concerning the effect of rest periods on concrete tested under water. The present study was exploratory and not intended to completely define all aspects and behavior of concrete subjected to combinations of fatigue loading and rest period blocks under water. The results from this study indicated that rest periods are detrimental to concrete tested under water. This phenomenon was found to be more pronounced on high strength LWA concrete when tested in submerged condition under high confining pressure.

Due to certain time constraints, only a few parameters have been studied. It is suggested that more tests be conducted on LWA concrete with multiple rest periods. It was observed from this study that most of the damage of concrete occur only in the first few cycles of the loading block following the rest period. Therefore, a loading program that contains a multiple number of cycles per block is suggested.

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APPENDIX

WATER UPTAKE DATA

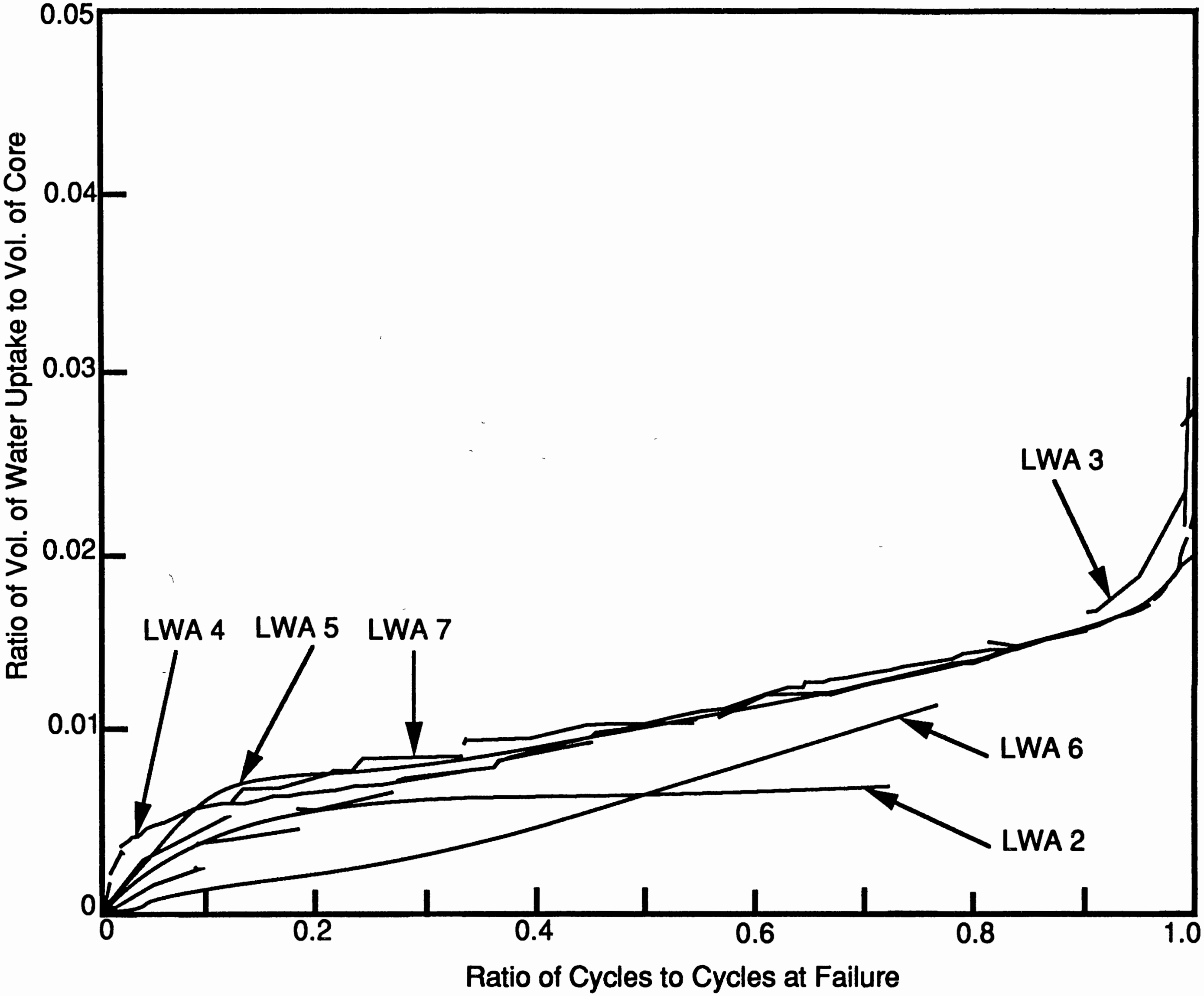

Figure A.1. Water Uptake of LWA Concrete at a Confining Pressure of 7.0 Mpa

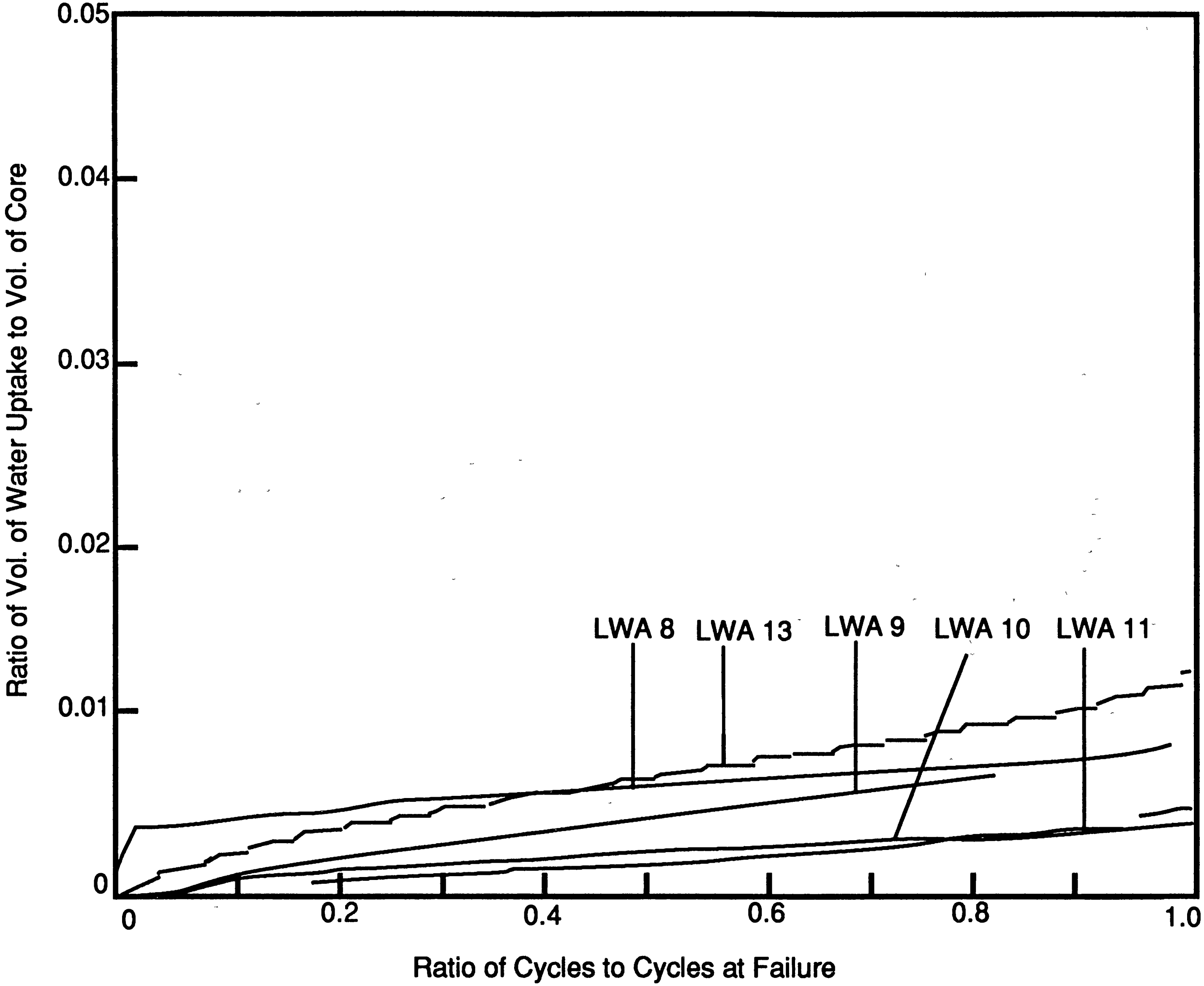

Figure A.2. Water Uptake in LWA Concrete at a Confining Pressure of 0 Mpa

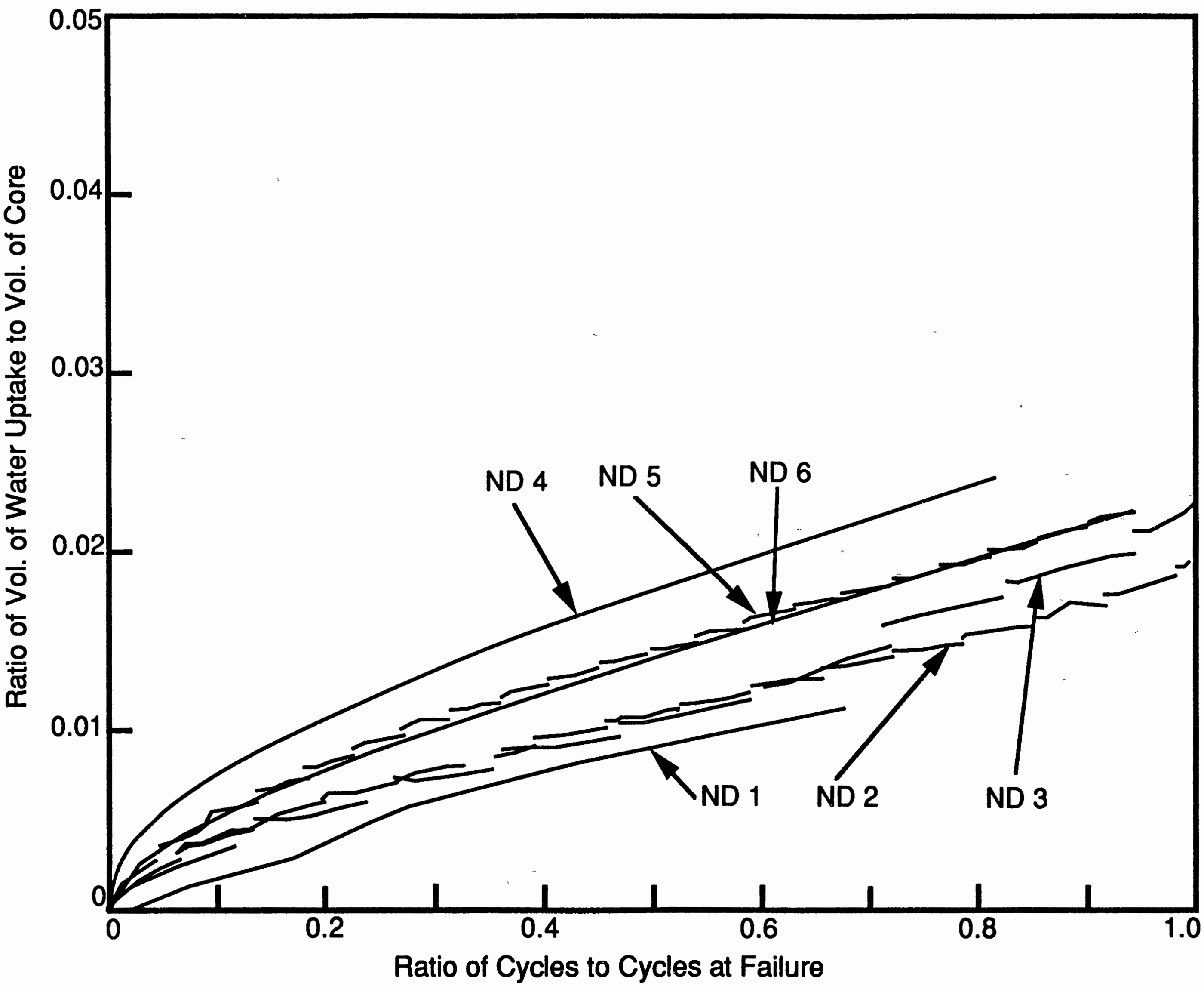

Figure A.3. Water Uptake of ND Concrete at a Confining Pressure of 7.0 Mpa

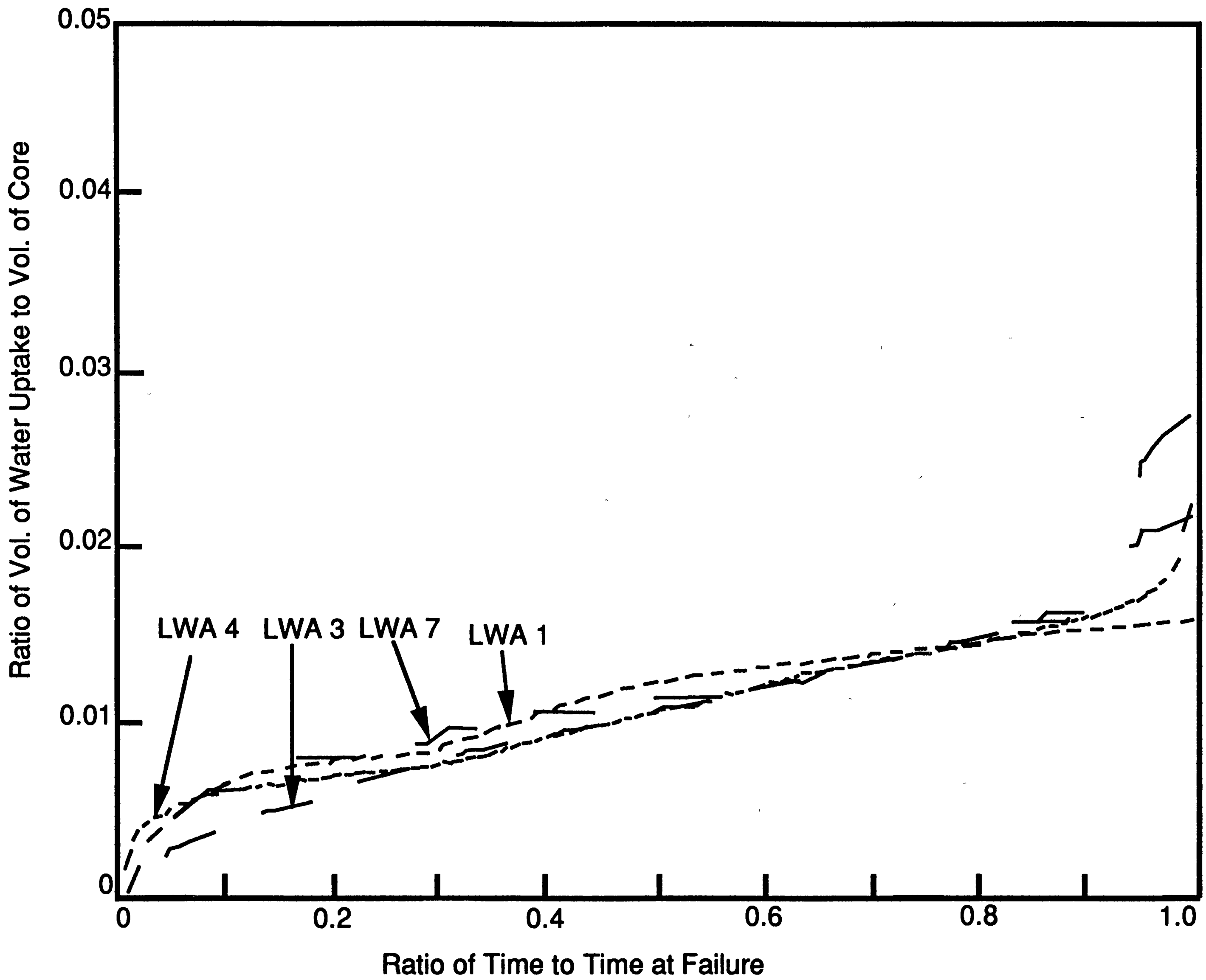

Figure A.4. Water Uptake of LWA Concrete at a Confining Pressure of 7.0 Mpa During Rest Periods

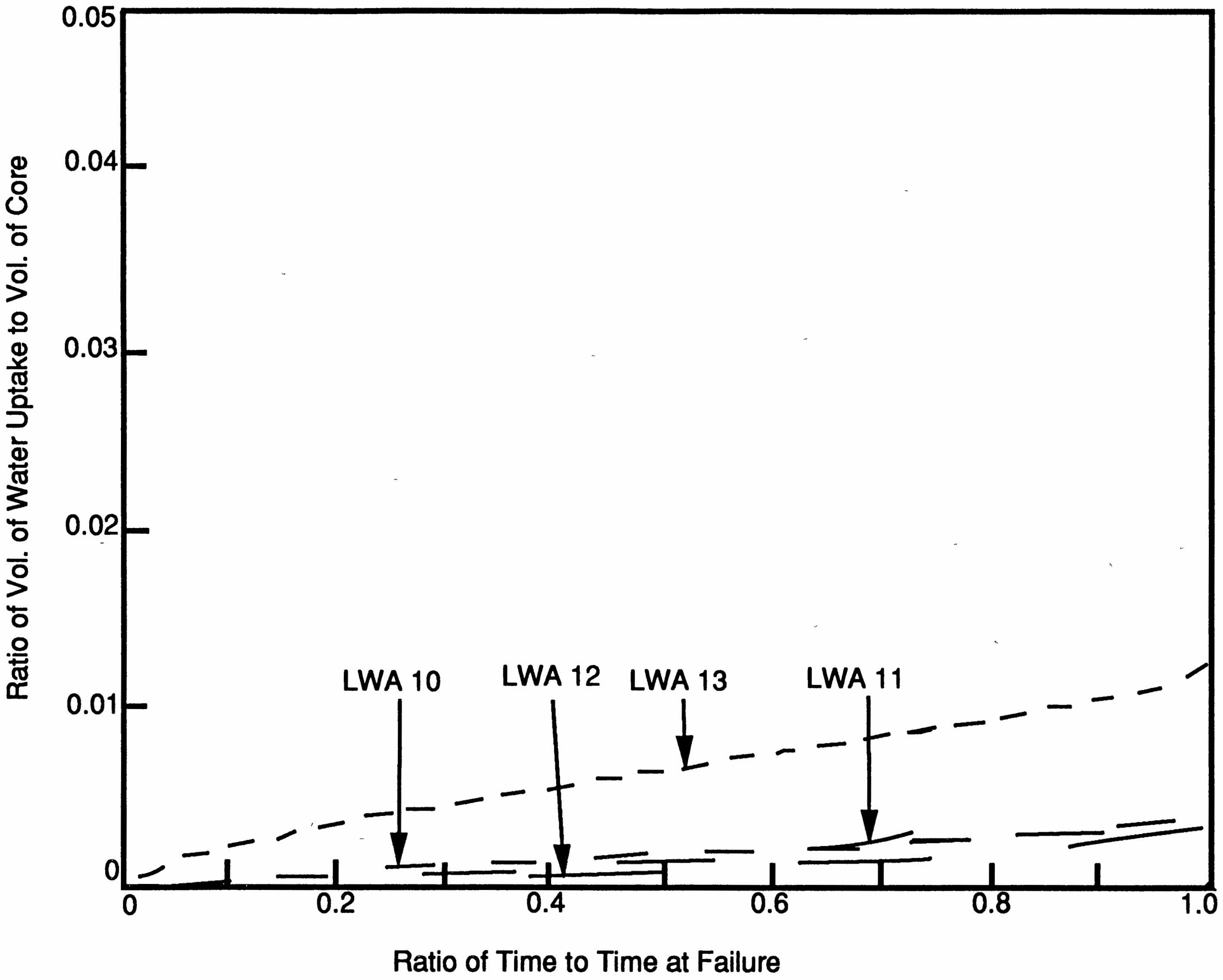

Figure A.5. Water Uptake of LWA Concrete at a Confining Pressure of 0 Mpa During Rest Periods

VITA

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